A repeated cross-sectional study of a biophilic building's effects on workers' perception of indoor environmental quality, health, well-being and productivity

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A repeated cross-sectional study of a biophilic building's effects on workers' perception of indoor environmental quality, health, well-being and productivity

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ABSTRACT

The study aimed to investigate the sustained effects of a case study biophilic designed building, The Enterprise Centre (TEC) in the UK, on its permanent workers' satisfaction with the indoor environmental quality (IEQ) and their health, well-being and productivity. A repeated cross-sectional research design, following the Building Use Studies (BUS) Methodology, was used with two data collection periods 12 and 24 months after building occupation with participation rates of 86 % and 97 % respectively. Results showed high and sustained satisfaction with IEQ, including thermal comfort, acoustics, lighting, and air quality. Workers consistently reported improved health and well-being, with productivity gains of 12.98 % amongst the 12-months cohort and 9.17 % for the 24-months cohort. This study contributes novel insights by: (1) providing evidence of biophilic design's sustained impact over time, an area with limited existing research; (2) evaluating combined biophilic strategies at full-building scale (including natural materials and colours, connection with nature, outdoor views, natural light and air, and climate-aligned indoor conditions) rather than isolated biophilic interventions; and (3) establishing new insights into the effects of biophilic design on occupant health, well-being, and productivity. The positive outcomes suggest that biophilic design could be successfully integrated into future buildings and spaces to improve satisfaction with IEQ and enhance workplace health and performance.

1. Introduction

There is significant evidence that the design and operation of the places that people work has an effect on their health and wellbeing [1–3] as well as their productivity [4,5]. Multiple studies have demonstrated that improvements in occupants' thermal, visual and acoustic comfort, as well as the indoor air quality (IAQ), collectively referred to as indoor environmental quality (IEQ), increase occupant satisfaction and are also linked to positive occupant health and wellbeing and productivity outcomes. For example, Gend et al. [6] investigated the effects of the thermal environment on occupants' IEQ perception and productivity, and established that optimal productivity was obtained when people felt "neutral" or "slightly cool", and an increase of thermal satisfaction had a positive effect on productivity. Falgueiras et al. [7] indicated that poor IAQ and thermal comfort are linked with sick building syndrome

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symptoms in workers. A comprehensive review of previous studies is presented in Pei et al. [8].

Other studies have focused on IEQ conditions in sustainable buildings (also known as green buildings) and their effects on their occupants [9–13]. Allen et al. [14] simulated different IEQ conditions to evaluate their impact on occupants' higher-order cognitive function and concluded that cognitive function was significantly better in buildings where IEQ requirements met a sustainability certification (i.e. U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) [15]) than in conventional building conditions. Singh et al. [16] established improvements in asthma and depression symptoms, and perceived productivity in LEED buildings. As a result, increasing efforts are being made in the architecture, engineering and construction (AEC) industry to apply building design methods and standards (e.g. the Building Research Establishment Environmental Assessment Method (BREEAM) [17] from the United Kingdom, Green Star from Australia [18] and LEED from the United States) that contribute to the improvement of a building's IEQ, with the aim to increase occupant satisfaction, as well as deliver positive occupant health and wellbeing, and productivity outcomes.

Similarly, in recent years, designers have placed increasing attention on the integration of biophilia into the design of building interiors encouraged by the growing robust evidence of biophilia's potential benefits to people. Biophilia describes humanity's preference for natural environments, an instinct deeply rooted in the brain [19,20] and the result of the majority of human evolution having taken place outdoors [21]. Kellert [22] was the first to refer to building design practice aimed at creating positive relationships between humans and the natural environment as "biophilic design". A number of biophilic design frameworks have been developed which summarise and classify natural design features that can be used in building design activities. For example, Kellert and Calabrese's [23] theoretical framework defines five fundamental principles of biophilic design. Terrapin Bright Green [24] provide a "14 patterns of biophilic design framework" with three categories of implementation linked to specific aspects of health and wellbeing for a range of environments. Beatley [25] developed a macro scale framework for the biophilic city incorporating urban planning, population health and wellbeing, urban landscapes, etc. Most recently, Thomas and Xing [21] presented a holistic design framework for the evaluation and implementation of biophilia in the built environment which consists of three main categories of biophilic design: direct contact with nature, indirect contact with nature, and space and place. Within these categories, twenty-four methods of application of biophilic design are detailed.

Biophilia has been demonstrated to have direct and indirect positive effects on people's physical and psychological health [26–30], their work and study performance [31,32] and productivity [27,33–35]. Yin et al. [28] used a randomized crossover study where participants experienced for 5 min an indoor environment featuring biophilic design elements and one without, in reality and virtually using virtual reality (VR), and found that exposure to biophilic design elements, including indoor plants, natural materials and external views of nature, resulted in decreased negative emotions and blood pressure, improved short-term memory and increased positive emotions. Yin et al. [29,30] also exposed participants for a short time (10 min) to biophilic elements using virtual reality offices with simulated green plants, natural light and views, products made of or looking like natural materials and furniture in biomorphic shapes, and observed reduced stress, anxiety and improved creativity for the participants exposed to the biophilic elements. Lei et al. [33] undertook a repeated-measures study in experiment rooms to evaluate the sensitivity of office workers' performance on the changes of greenery dose and found that 12 % was the optimum biophilic dose to improve people's psychological and physiological health and productivity. Berger et al. [36] used a web-based photo-questionnaire to investigate people's preferences and responses to a range of indoor plants to determine if the plant appearance and shape affects people's perception of its impact on IAQ, relative humidity or subjective well-being. Using a similar photographic method, White et al. [37] investigated whether the presence of water in both natural and built environments would have a positive impact on people, and found that both natural and built scenes containing aquatic elements were associated with higher preferences, greater positive effect and higher perceived restorativeness than those without water. A comprehensive review of previous studies is presented in Zhong et al. [26].

Whilst the majority of studies have explored the impact of one or a small combination of biophilic elements in control environments (through VR environments or experimentation rooms), studies of the impact of biophilia on occupants in real working environments or at a building scale remain limited. Lei et al. [27] used a single point post-occupancy evaluation (POE) questionnaire to assess the impact of various biophilic design attributes present in two pre-selected offices within a building, on the health and wellbeing of occupants at their workplace. Nieuwenhuis et al. [38] studied the impact of the presence of plants into an office and established improvements in perceived concentration and productivity as well as actual productivity (less time taken to complete a task and less errors made). Hahn et al. [32] investigated whether introducing and removing living plants within an office environment can affect occupants' perceived health, well-being and performance metrics. The study took place in multiple offices and break-out spaces in a modern office building and established that introducing plants into offices had significant positive effects on occupants' perceived attention, creativity and productivity, however, there was no indication of effects on perceived health, tiredness, motivation or well-being. Studies exploring biophilia applied at a building scale primarily focus on WELL buildings. The WELL Building Standard [39] assimilates a number of biophilic design principles as either requirements or recommendations in the certification process. Ildiri et al. [40] studied the pre- and post-occupancy survey responses of workers moving to a WELL certified office and found that occupant satisfaction and their perceived health, well-being, and productivity increased after the move. Candido et al. [41] and Licina and Yildirim [42] found similar positive outcomes for workers in WELL certified buildings, although the latter reported insignificant differences in productivity and sick building syndrome symptoms. Finally, Licina and Langer [43] identified increased satisfaction with the IAQ in WELL certified buildings, despite the air quality not being significantly different from the non-WELL certified buildings used as comparisons in the study.

1.1. Research gaps

Whilst the existing literature provides insights into the effects of biophilic design on people's perceptions of IEQ, as well as their health, well-being and productivity, significant research gaps still exist that will be addressed in the current paper.

First, previous studies have mostly been undertaken using virtual reality or imagery in controlled environments. Studies completed in real settings are limited, and the findings have predominantly relied on single point post-occupancy evaluations (POE) or short-term controlled experiments. As a result, there is a lack of empirical evidence regarding the long-term sustainability of the effects of biophilic design in buildings. The current study addresses this gap by examining the effects of a whole real-world biophilic building on its occupants over a two-year period using a repeated cross-sectional study providing a novel and more thorough understanding of whether the effects of biophilic design are sustained over time.

Second, existing studies on biophilic design often focus on isolated features, such as increased indoor planting or access to outdoor views, rather than assessing the combined effects of multiple biophilic strategies implemented at the full building scale. While research on WELL-certified buildings [40–43] may offer some insights into the combined effects of biophilia at scale, these findings are limited by the optional nature of many biophilic components within the certification framework and as such, it is often unclear which and the extent of biophilic features the studied buildings incorporated. This study advances the current body of knowledge by investigating the combined effects of multiple biophilic design strategies applied holistically across an entire building. By moving beyond the analysis of isolated elements and accounting for actual implementation, the research provides evidence of the effects of biophilia at scale.

Third, whilst extensive research has explored the influence of IEQ on occupant satisfaction, there remains a notable gap concerning the specific effects of biophilic design on occupant health, well-being, and productivity. The current literature indicates that empirical studies within biophilic designed buildings are currently scarce [28,33] and constitutes a significant gap. The present study addresses this gap by examining an exemplary biophilic case study, thereby offering empirical evidence of the effects of biophilic design in buildings providing an important contribution to knowledge.

1.2. Aim and research questions

The aim of this study was to investigate the perceived IEQ, health and well-being and productivity of occupants working in The Enterprise Centre (TEC), an exemplary biophilic non-domestic building in the UK.

The study addresses the following research questions:

1. How satisfied with the indoor environmental quality are the occupants working in a biophilic building?
2. Does working in a biophilic building have an effect on occupants' health and well-being and productivity?
3. Is satisfaction with the indoor environmental quality and improvements in health and well-being and productivity sustained over time?

2. Methodology

2.1. The Enterprise Centre and its biophilic design principles

The Enterprise Centre (TEC) at the University of East Anglia (UEA) is an exemplar of sustainable building design and has been referred to as the UK's greenest building [44]. The building is Passivhaus certified and achieved a Building Research Establishment Environmental Assessment Method (BREEAM) Outstanding rating, with a score of 93 %. TEC has a gross floor area of 3426 m^2 providing a variety of commercial spaces for start-up and local businesses as well as spaces used by the UEA for teaching and learning, including a 300-seat lecture theatre. A detailed description of the building including the envelope and glazing U-values and building services is available in Korsavi et al. [45]. Since completion, the authors of this paper, one of whom was the TEC Deputy Project Director at UEA and oversaw the design and construction of the building, have been undertaking an ongoing assessment of the building's actual performance in use. An earlier published paper has confirmed its high energy and carbon performance credentials in operation [45].

TEC is characterised by its ultra-low embodied carbon, with total net embodied emissions calculated at less than 500 $kgCO_2/m^2$ throughout its 100 year lifecycle, which is significantly lower than other comparable buildings designed to 'best practice' standards, that can expect to have already emitted 800–900 $kgCO_2/m^2$ on their first day of occupation. The ultra-low embodied carbon was attained by using 70 % natural and bio-renewable materials for the construction technologies which were supplied from local sources.

TEC uses a range of biophilic design methods that can be categorised as: the use of natural materials and colours; evocation of nature; connection with outdoor natural environment; increasing natural light and air; cultural and ecological attachment; and indoor environmental conditions in tune with the prevailing outdoor weather. Table 1 describes the full range of biophilic features incorporated into the building across each category, while Figs. 1–3 present annotated illustrative images of these features.

Other noteworthy features that could have affected the occupants' perception of the IEQ in the building were: there was no mechanical cooling system in the areas used by the permanent workers; only 2–2.5 h of heating provided by a wet heating system on cold mornings to increase the temperature before occupation; minimum continuous ventilation with heat recovery is used with the volume of air only increased in summer when 26 °C or 1500 ppm CO_2 concentration setpoints were exceeded. Ventilation was also provided by the manual opening of the triple-glazed windows. The building used a night purge ventilation strategy for cooling with the high thermal mass exposed concrete ground floor storing heat during the day and releasing it at night through automated clerestory

Table 1
The biophilic features used in The Enterprise Centre.

Biophilic design principle	Explanation of principle	Practical implementation of principle in TEC
Use of natural materials and colours	Integrating natural materials such as wood, stone and natural textiles into a building to evoke the textures, colours and sensory experiences of the natural world.	• Almost all the building made of timber, with exposed and concealed cellulose. • Internal walls and some ceilings finished with timber slats and wood wool acoustic panels. • Dry internal wall linings combined with natural wall coverings: Nettle fabric, earth (clay) board, locally sourced reed boards and a rustic hemp and lime render. • Solvent-free organic paints on walls and ceilings. • External wall cladding panels of Norfolk Long Straw and recycled wood. • Timber façade brise soleil. • Reed thatched clerestory roof. • Glulam columns of Larch & Spruce timber, and Birch plywood balustrades and staircases. • "Hit and miss" strips of timber to walls and some ceilings, and blown cellulose on the ceilings dampens reverberating noise. • Diamond polished concrete floors allowing the natural stone content pattern to shine through. • First floors covered in linoleum releasing the natural smell of linseed oils. • Hemp fabric to the lecture theatre seating and cladding to first floor seating POD.
Evocation of nature	Designing building elements that symbolically or abstractly reference natural forms, patterns and processes rather than directly using natural elements.	• Tall slender fenestration to the west punctuated by similar sized panels of long straw to emulate and frame the tall pinewood trees adjacent. • Roof top waterfall cascading onto stone cobbles in the central courtyard. • Main entrance canopy supported by tall slender glulam poles emulating the larch trees from which they were formed.
Connection with outdoor natural environment	Creating visual, physical and sensory access to nature by integrating elements such as large windows, balconies, courtyards, green roofs and views of landscapes.	• Retention of adjacent hedges with minimal penetrations to the east. • Southern landscape of wildflower meadow, and a northern landscape developed as a physic garden. • The building sits in clean edged flint beds echoing the form of the building providing a textured frame for the architecture. • Flint beds sparkle and bubble when it rains, before the water drains away into the courtyards bed of thriving Norfolk Reeds. • Roof top terrace, central to the courtyard and framed and sheltered on three sides by the buildings structure. • From practically every window or door are views of trees, grass or hedgerows, with the first floor enjoying the green landscapes beyond the buildings boundary. • Internally, the extensive use of cellulose sprayed onto some ceilings and insulation hidden behind "hit and miss" timber strips to walls and ceilings, significantly absorbing reflected sounds and removing echoes and reverberation, providing spaces with calm non-intrusive background sounds.
Increased natural light	Maximising natural daylight within indoor spaces by integrating elements such as large windows, skylights, light wells and reflective surfaces and reducing reliance on artificial lighting.	• E-shaped building form with floor-to-ceiling heights in excess of 3.3m allows natural light to more effectively penetrate interior spaces. • The majority of windows facing south, capturing natural daylight, and solar warmth in winter sun. • Tall unbroken windows spanning both floors allow natural light to penetrate. • Clerestory roof windows with angled ceilings deflect natural light to the north side of both wings, and regular openings within the first floor allows the light to penetrate the north side of the ground floors too. • Offices, seminar and teaching rooms provided with "borrowed light" panels above internal doors and glazed partitions, maximising the reflected clerestory light.
Increased natural ventilation	Allowing fresh air to flow naturally into the building using openings such as windows, vents, atriums and courtyards, enhanced by building orientation and passive airflow strategies.	• E-shaped building form with narrow wings allows natural fresh air to more effectively penetrate interior spaces. • Rooms served with variable air volume (VAV) mechanical ventilation with warm stail air passing out through a thermal wheel to temper the fresh cool air being drawn into the building and filtered before being distributed.

(*continued on next page*)

Table 1 (*continued*)

Biophilic design principle	Explanation of principle	Practical implementation of principle in TEC
		• Numerous window openings in every room allow occupants the choice of natural ventilation. • Automated clerestory roof windows used to night purge warm air, with fresh cool air being drawn in from the ground floor security grilles to cool the ground floor concrete slab. • The stored coolth in the ground floor slab used to temper the air throughout the building, retaining a stable temperature throughout occupied periods.
Cultural and ecological attachment	Designing spaces that reflect and honour the unique natural and cultural context of the local ecology, climate, materials and traditions creating a sense of belonging, identity and stewardship.	• Local East Anglian materials, such as timber from Elveden and Thetford forests, flint cobbles from Holt, long straw from Norfolk and reed from north Suffolk, used in the building's design aesthetic. • Reeds for the clerestory roofs thatched and 294 long straw external facade cassettes thatched by a team of local thatchers. • Demolition rubble from the 200-year-old St. Andrew's Hospital crushed, graded at St. Andrews and transported the 19 miles to UEA to form the building's sub base.
Indoor conditions aligned with outdoor weather	Designing indoor spaces that allow occupants to experience and adapt to the natural variability of outdoor conditions, such as changes in temperature, light and airflow creating a stronger connection to natural rhythms.	• E-shaped building form maximises occupants direct contact with natural outdoor conditions. • CO_2 sensors control the VAV ventilation system. • A two light display in every room indicates green when windows can be opened and turns red when windows should be closed to allow the VAV systems to cope with the airflow demands. • Deep window reveals provide the fenestration with summer shade, and low winter sun can be briefly shielded by drawing blinds where necessary. • Ground floor concrete slab cooled overnight by night purging and drawing in cool air at low level. Stored coolth is used to temper the air throughout the building, retaining a stable temperature throughout occupied periods.

Fig. 1. Annotated aerial view of The Enterprise Centre by ARCHITYPE [44] (Note: a. Retained hedgerow; b. Physic garden; c. Flint cobbled moat; d. Vertical windows emulating pine stand; e. Courtyard and terrace; f. Larch glulam poles; g. Long straw cladding; h. Reed thatch; i. E-shaped building form).

windows and manual opening of ground floor doors. Natural light was provided through windows, skylights and clerestory roof. The office areas had built-in individual desk lamps as their primary artificial lighting source with low illuminance LED strips at a ceiling level for background lighting. The artificial lighting was controlled by passive infrared (PIR) sensors.

In line with the building's Passivhaus status, TEC achieved an airtightness of 0.21 $m^3/(m^2.h)$ @50 Pa, which was three times better than what is required to achieve Passivhaus certification. High airtightness is essential to reduce energy losses [46,47] but has been shown to contribute to possible issues with summertime overheating [48] and IAQ [49].

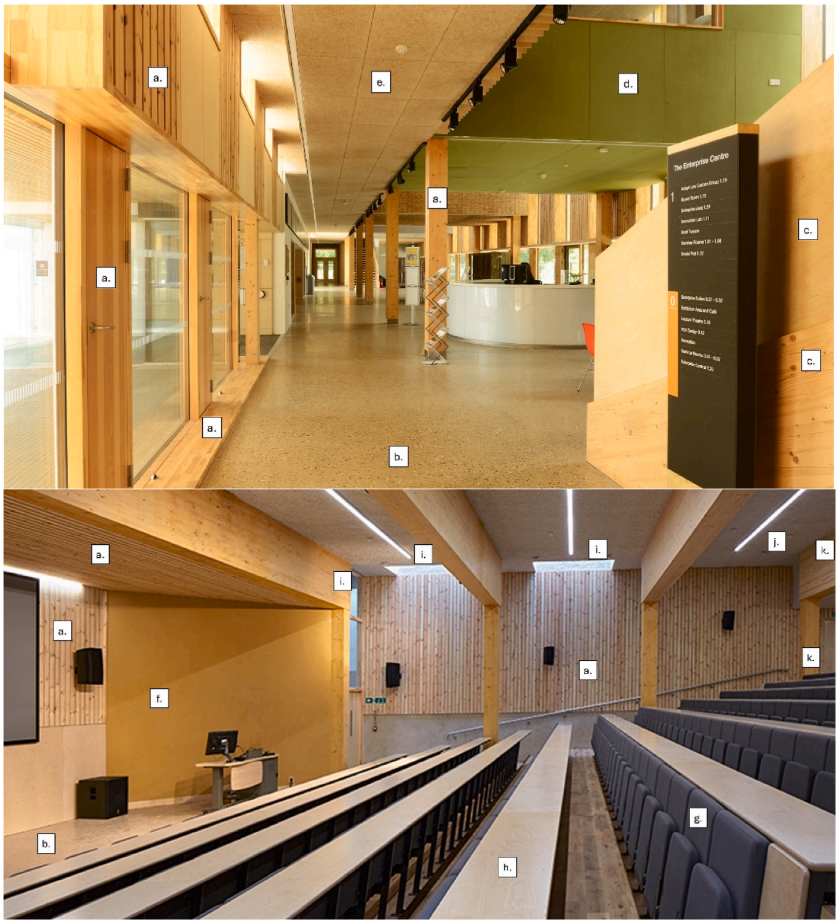

Fig. 2. Annotated internal spaces of The Enterprise Centre by ARCHITYPE [44] (Note: a. Natural finish timer; b. Polished concrete floor; c. Ply and Glulam staircase and balustrade; d. Nettle fabric cladding board; e. Strawboard removable ceiling tiles; f. Clay plaster walls and natural paints; g. Hemp fabric seating; h. Birch ply writing shelf; i. Sky lights and borrowed lights; j. Spray on cellulose sound insulation; k. Glulam structural beams and columns).

2.2. Building Use Studies methodology

The Building Use Studies (BUS) Methodology [50] was used to gather data from occupants' working in the TEC building about their perception of the typical indoor environmental conditions, as well as their perceived health and well-being and productivity. TEC provides a hub for businesses to rent office space in either an open plan office or private two to six-person offices. The current study only collected data from the permanent office workers that were regularly exposed to the biophilic elements of the building. The BUS survey has a standard set of up to 45 quantitative and qualitative questions gathering data on a range of IEQ criteria including air quality, lighting, temperature, noise and overall comfort, as well as the health and well-being and productivity of workers, and building design criteria. Respondents are also asked some background information, such as age, sex, length of time working in the building and whether they are sat next to a window in their normal working area. The BUS survey is a validated survey [51] and has been estimated to have been used in a minimum of 300 previous publications [52] and has been continuously developed over 30 years since its first use as part of the seminal Post-occupancy Review Of Buildings and their Engineering (PROBE) project in the UK in the 1990s [52,53].

The BUS survey questions used in the current paper are presented in Table 2. Participants were asked to rate the IEQ criteria on Likert scales of 1–7. It should be noted that the descriptions of points 1 and 7 vary between questions. For example, the criterion 'overall perception of winter temperature' ranges from 1 (uncomfortable) – 7 (comfortable), therefore, the higher the mean score the better. Whereas, the criterion 'humidity of air in winter' ranges from 1 (dry) – 7 (humid), therefore a mean score of 4 is preferable.

Respondents were asked to rate on a 9 point Likert scale their perceived increase or decrease in productivity at work as a result of the environmental conditions in the building, from 1 (decreased 40 % or more) – 9 (increased 40 % or more). A mid score of 5 indicated neither an increase or decrease in productivity. The self-reported productivity question used in this study is derived from the validated BUS survey. A recent scoping review [51] found that self-report occupant questionnaires are the most commonly used method for assessing productivity in buildings, with 35 out of 38 reviewed studies employing them. Respondents are asked to evaluate their

Fig. 3. Annotated internal courtyard of The Enterprise Centre by ARCHITYPE [44] (Note: a. Larch glulam poles; b. Courtyard lecture theatre with terrace above; c. Clay pavement sets; d. Norfolk flint cobbled moat; e. Recycled laboratory bench façade; f. All façade windows; g. Wooden brise soleil; h. Operable windows behind security grilles).

productivity against a baseline of their experience of using buildings in general.

Furthermore, participants reported on a 7 point Likert scale whether they felt more or less healthy in TEC when compared with their experience of using other buildings. A mid score of 4 indicated that their health and well-being was similar to when they used other buildings, points 5–7 indicated an improved health and well-being and 1–3 poorer health and well-being.

Responses to the BUS survey were collected in the TEC building in two data collection periods 12 and 24 months after initial building occupation. The survey forms were distributed by two researchers from the Building Services Research and Information Association (BSRIA), a UK-based testing, instrumentation, research and consultancy organisation, providing specialist services in construction and building services engineering. All permanent occupants of the building on the days of the surveys received a form to complete. 50 surveys were completed at 12 months (86 % response rate of the 58 permanent occupants) and 38 surveys at 24 months (97 % response rate of the 39 permanent occupants), referred in this paper to as the '12-months cohort' and '24-months cohort', respectively. It is important to note that whilst the sample sizes are relatively small, these represent an almost complete census of the study's target population, rather than a small random sample seeking to draw generalised findings of a larger population. This approach is consistent with case study research methodologies and whilst caution should be applied when extrapolating beyond this case study, the findings can be valuable for theory-building, contextual analysis and informing practice within comparable environments [54,55].

The participants of the 12-months cohort were: 56 % (28) male and 44 % (22) female; 72 % (36) were aged 30 or over and 28 % (14) were under 30 years; 64 % (32) had worked in the building for more than a year and 34 % (18) less than a year; and 68 % (34) sat next to a window whilst working and 34 % (16) did not sit next to a window. The participants of the 24-months cohort were: 55 % (21) male and 45 % (17) female; 66 % (25) were aged 30 or over and 34 % (13) were under 30 years; 61 % (23) had worked in the building for more than a year and 39 % (15) less than a year; and 61 % (23) sat next to a window whilst working and 39 % (15) did not sit next to a window.

2.3. Measured indoor and outdoor environmental conditions

The 12 and 24 months BUS surveys were both undertaken in summer (July). Although, respondents were asked to report their perceptions of the typical IEQ conditions in the building, it should be acknowledged that the prevailing indoor and outdoor conditions on the day of the survey may have affected their responses. Also, responses related to the winter may be subject to recall bias due to the time that had elapsed between the winter season and the survey. Therefore to provide some context to the results presented in the current paper, the environmental conditions at midday on the day of the 12 months survey were: outdoor temperature 25 °C; indoor temperature 24.5–25.5 °C and indoor relative humidity (RH) 48–50 %. At 24 months they were: outdoor temperature 23.5 °C; indoor temperature 22.6–24.1 °C and indoor RH 39–40 %. The data were collected using a Vaisala HM70 handheld humidity and temperature meter with a temperature accuracy at +20 °C of ±0.2 °C and RH accuracy of ±1 %.

2.4. Data analysis

This paper analyses the perceptions of permanent TEC workers regarding the impact of the building's biophilic design on indoor

Table 2
Building Use Studies survey questions used in the current paper.

Questions	Participant response scales
Participant background	
What is your age?	Age
What is your sex?	Male/Female
How long have you worked in the building?	Years
Do you sit next to a window at your normal work area?	Yes/No
Indoor Environmental Quality	
Temperature	
How would you describe typical temperature conditions in the building in winter?	Temperature in winter overall: 1 (uncomfortable) – 7 (comfortable) Temperature in winter: 1 (too hot) – 7 (too cold) Temperature in winter: 1 (stable) – 7 (varies during day)
How would you describe typical temperature conditions in the building in summer?	Temperature in summer overall: 1 (uncomfortable) – 7 (comfortable) Temperature in summer: 1 (too hot) – 7 (too cold) Temperature in summer: 1 (stable) – 7 (varies during day)
Lighting	
How would you describe the quality of the lighting in the building? *This question refers to conditions all year round.*	Lighting overall: 1 (unsatisfactory) – 7 (satisfactory) Natural light: 1 (too little) – 7 (too much) Artificial light: 1 (too little) – 7 (too much) Glare from sun and sky: 1 (none) – 7 (too much) Glare from artificial lights: 1 (none) – 7 (too much)
Acoustics	
How would you describe the noise in the building? *This question refers to conditions all year round.*	Acoustics overall: 1 (unsatisfactory) – 7 (satisfactory) Noise from inside: 1 (too little) – 7 (too much) Noise from outside: 1 (too little) – 7 (too much)
Air quality	
How would you describe typical air conditions in the building in winter?	Air in winter overall: 1 (unsatisfactory) – 7 (satisfactory) Air humidity in winter: 1 (dry) – 7 (humid) Air freshness in winter: 1 (fresh) – 7 (stuffy) Air odour in winter: 1 (odourless) – 7 (smelly) Air movement in winter: 1 (still) – 7 (draughty)
How would you describe typical air conditions in the building in summer?	Air in summer overall: 1 (unsatisfactory) – 7 (satisfactory) Air humidity in summer: 1 (dry) – 7 (humid) Air freshness in summer: 1 (fresh) – 7 (stuffy) Air odour in summer: 1 (odourless) – 7 (smelly) Air movement in summer: 1 (still) – 7 (draughty)
Productivity	
Estimate how you think your productivity at work is decreased or increased by the environmental conditions in the building? *Please try to evaluate this building with respect to your experience of using buildings in general.*	Perceived productivity increase/decrease: 1 (−40 % or more) – 9 (+40 % or more)
Health and Well-being	
Do you feel less or more healthy when you are in the building? *Please try to evaluate this building with respect to your experience of using buildings in general.*	Perceived health and well-being: 1 (less healthy) – 7 (more healthy)
Overall comfort	
All things considered, how do you rate the overall comfort of the building's environment?	Overall comfort: 1 (unsatisfactory) – 7 (satisfactory)
Building design	
All things considered, how do you rate the building's design overall?	Overall building design: 1 (unsatisfactory) – 7 (satisfactory)
How do you rate the image that the building as a whole presents to visitors?	Image to visitors: 1 (poor) – 7 (good)

environmental quality, as well as on their health, well-being, and productivity. The study used a repeated cross-sectional study design to collect data from two cohorts of the permanent workers at two time points over a two year period within the same building setting (the 12-months and 24-months cohorts). This approach allowed trends or changes at the worker population level to be studied. Descriptive statistics (mean and standard deviation) of the examined variables are analysed for the 12-months and 24-months cohorts separately at the specific point in time when the BUS surveys were completed. Also, independent sample t-tests are used to assess changes over time in the examined variables between the 12-months and 24-months cohorts. A *t*-test compares the means of two sets of data collected at different time points and assesses whether any observed difference in mean is statistically significant, suggesting a real change rather than just random variation. A p-value from the *t*-test below 0.05 indicates that the change in mean over time is likely not due to chance. In the context of the current paper, non-significant p-values (greater than 0.05) are more important as they indicate that the positive effects of the building's biophilic design reported by the 12-months cohort had been similarly observed by the 24-months cohort and were therefore sustained over time.

3. Results

3.1. Indoor environmental quality

3.1.1. Temperature

The BUS survey results for the 12 and 24-months cohorts related to indoor temperature in winter and summer are shown in Fig. 4. The occupants working in the building assessed the TEC building as slightly cool in winter as the mean values of both cohorts exceeded 4 (a value of 4 indicates a neutral temperature that is neither too hot nor too cold). A significant *t*-test result (t (74) = −2.297, p = 0.024) (Table 3) also implies that occupants perceived the building as colder in the second winter of occupation (mean = 5.34, SD = 1.04) than the first winter (mean = 4.82, SD = 0.95). In summer, both cohorts evaluated the indoor temperature to be slightly warm (12-months cohort: mean = 3.49, SD = 0.94; 24-months cohort: mean = 3.61, SD = 0.97). Concerning the stability of temperature, mean values around 4 were obtained in winter and summer for both cohorts, implying that changes in indoor temperatures were well balanced between stability and variation throughout the day in both colder and hotter seasons. Overall the temperature in both winter periods was evaluated as fairly comfortable, although the winter experienced by the 12-months cohort (mean = 4.98, SD = 1.57) was considered more comfortable than that experienced by the 24-months cohort (mean = 4.41, SD = 1.86). Similarly, the overall temperature in summer was judged as fairly comfortable, however the summer assessed by the 24-months cohort (mean = 5.31, SD = 1.40) was significantly more comfortable than that assessed by the 12-months cohort (mean = 4.59, SD = 1.41; t (69) = −2.156, p = 0.035). Overall, the workers appeared to be generally satisfied with the thermal environment in TEC and for the majority of the variables investigated, non-significant *t*-test results (Table 3) indicated that their level of satisfaction was sustained over the first two years of occupation.

3.1.2. Lighting

The availability of natural light in the TEC building was evaluated as neither too little nor too much with mean values close to 4 for by both cohorts (12-months cohort: mean = 3.75, SD = 1.10; 24-months cohort: mean = 3.87, SD = 1.21). There was also strong agreement between occupants working in the building on the adequacy of natural light as indicated by the narrow box plots. The level of artificial light was considered by the building occupants as slightly less than desired by both cohorts (12-months cohort: mean = 3.40, SD = 1.25; 24-months cohort: mean = 3.16, SD = 1.33). The occupants reported that there was some glare from natural light sources but not at excessive levels. Similarly, there was some glare from the artificial lights but this was considered at a lower level than that from natural light. Overall the lighting was assessed positively by the occupants working in TEC (12-months cohort: mean = 4.15, SD = 2.01; 24-months cohort: mean = 4.57, SD = 1.92) (Fig. 5). Non-significant *t*-test results (Table 3) for all variables indicates that the workers' satisfaction with the lighting environment in the building was consistent over the two years studied.

3.1.3. Acoustics

The occupants working in the building evaluated the noise from both inside and outside the building close to optimal, neither too much nor too little noise (value of 4). The occupants' assessment of the inside and outside noise was also notably consistent over the two years evaluation. The overall acoustics of the building was evaluated very positively with a mean of 5.70 (SD = 1.19) by the 12-

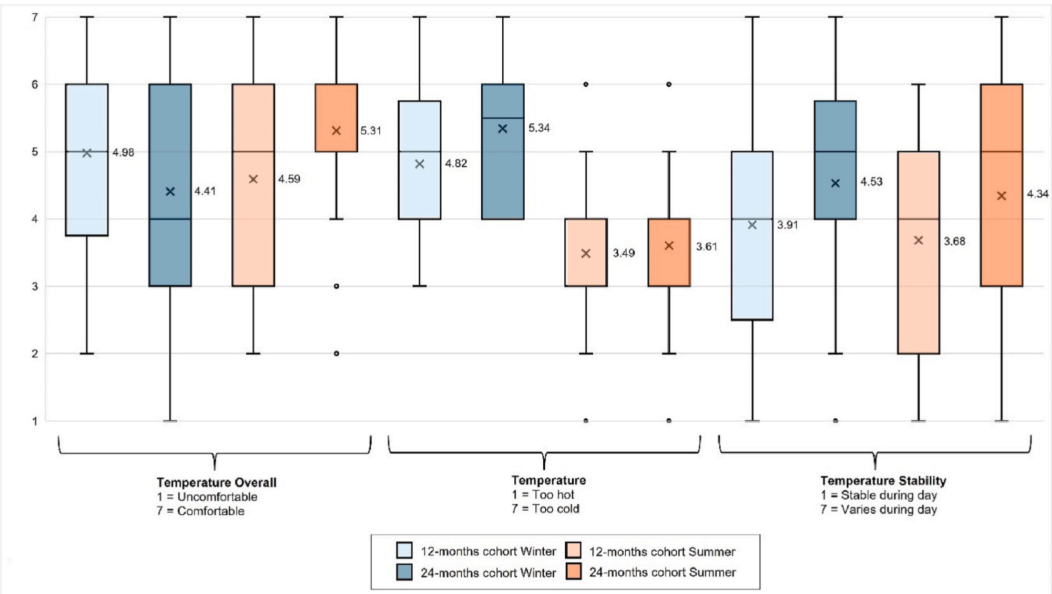

Fig. 4. Indoor temperature in summer and winter.

Table 3
12 and 24-months cohort data for indoor environmental quality, health and wellbeing and productivity in The Enterprise Centre.

Performance criteria	12-months cohort		24-months cohort		t-test[†]
	N	Mean (SD)	N	Mean (SD)	
Indoor Environmental Quality					
Temperature					
Temperature in winter overall: 1 (uncomfortable) – 7 (comfortable)	46	4.98 (1.57)	32	4.41 (1.86)	$t\,(76) = 1.465$, $p = 0.147$
Temperature in summer overall: 1 (uncomfortable) – 7 (comfortable)	39	4.59 (1.41)	32	5.31 (1.40)	$t\,(69) = -2.156$, $p = 0.035$*
Temperature in winter: 1 (too hot) – 7 (too cold)	44	4.82 (0.95)	32	5.34 (1.04)	$t\,(74) = -2.297$, $p = 0.024$*
Temperature in summer: 1 (too hot) – 7 (too cold)	39	3.49 (0.94)	33	3.61 (0.97)	$t\,(70) = -0.527$, $p = 0.600$
Temperature in winter: 1 (stable) – 7 (varies during day)	45	3.91 (1.72)	32	4.53 (1.55)	$t\,(75) = -1.628$, $p = 0.108$
Temperature in summer: 1 (stable) – 7 (varies during day)	38	3.68 (1.56)	32	4.34 (1.66)	$t\,(68) = -1.711$, $p = 0.092$
Lighting					
Lighting overall: 1 (unsatisfactory) – 7 (satisfactory)	48	4.15 (2.01)	37	4.57 (1.92)	$t\,(83) = -0.977$, $p = 0.331$
Natural light: 1 (too little) – 7 (too much)	48	3.75 (1.10)	38	3.87 (1.21)	$t\,(84) = -0.474$, $p = 0.637$
Artificial light: 1 (too little) – 7 (too much)	48	3.40 (1.25)	38	3.16 (1.33)	$t\,(84) = -0.853$, $p = 0.396$
Glare from sun and sky: 1 (none) – 7 (too much)	48	3.52 (1.73)	38	3.61 (1.48)	$t\,(84) = -0.240$, $p = 0.811$
Glare from artificial lights: 1 (none) – 7 (too much)	48	2.92 (1.40)	38	2.95 (1.41)	$t\,(84) = -0.101$, $p = 0.920$
Acoustics					
Acoustics overall: 1 (unsatisfactory) – 7 (satisfactory)	46	5.70 (1.19)	37	5.35 (1.21)	$t\,(81) = 1.302$, $p = 0.197$
Noise from inside: 1 (too little) – 7 (too much)	48	3.98 (1.06)	38	3.95 (0.90)	$t\,(84) = 0.147$, $p = 0.883$
Noise from outside: 1 (too little) – 7 (too much)	48	4.04 (0.82)	38	4.26 (1.12)	$t\,(84) = -1.050$, $p = 0.297$
Air quality					
Air in winter overall: 1 (unsatisfactory) – 7 (satisfactory)	45	5.22 (1.35)	31	4.58 (1.73)	$t\,(74) = 1.817$, $p = 0.073$
Air in summer overall: 1 (unsatisfactory) – 7 (satisfactory)	38	4.76 (1.20)	32	5.34 (1.47)	$t\,(68) = -1.821$, $p = 0.073$
Air humidity in winter: 1 (dry) – 7 (humid)	46	3.61 (1.00)	31	3.16 (1.21)	$t\,(75) = 1.766$, $p = 0.081$
Air humidity in summer: 1 (dry) – 7 (humid)	39	3.87 (1.47)	33	3.70 (1.51)	$t\,(70) = 0.496$, $p = 0.621$
Air freshness in winter: 1 (fresh) – 7 (stuffy)	46	3.28 (1.49)	32	3.47 (1.39)	$t\,(76) = -0.559$, $p = 0.578$
Air freshness in summer: 1 (fresh) – 7 (stuffy)	39	3.92 (1.46)	33	3.64 (1.56)	$t\,(70) = 0.806$, $p = 0.423$
Air odour in winter: 1 (odourless) – 7 (smelly)	46	2.93 (1.56)	31	2.58 (1.34)	$t\,(75) = 1.036$, $p = 0.304$
Air odour in summer: 1 (odourless) – 7 (smelly)	38	2.97 (1.59)	33	3.03 (1.40)	$t\,(69) = -0.158$, $p = 0.875$
Air movement in winter: 1 (still) – 7 (draughty)	46	2.85 (1.40)	31	3.39 (1.67)	$t\,(75) = -1.536$, $p = 0.129$
Air movement in summer: 1 (still) – 7 (draughty)	38	3.08 (1.34)	32	3.09 (1.28)	$t\,(68) = -0.047$, $p = 0.963$
Productivity					
Perceived productivity increase/decrease (%)	47	12.98 (16.01)	36	9.17 (16.97)	$t\,(81) = 1.048$, $p = 0.298$
Health and Well-being					
Perceived health and well-being: 1 (less healthy) – 7 (more healthy)	45	4.96 (1.31)	37	4.57 (1.12)	$t\,(80) = 1.422$, $p = 0.159$
Comfort					
Overall comfort: 1 (unsatisfactory) – 7 (satisfactory)	48	5.63 (1.02)	38	5.53 (1.16)	$t\,(84) = 0.419$, $p = 0.676$
Building design					
Overall building design: 1 (unsatisfactory) – 7 (satisfactory)	50	6.54 (0.65)	38	6.11 (0.89)	$t\,(86) = 2.649$, $p = 0.010$**
Image to visitors: 1 (poor) – 7 (good)	50	6.60 (0.61)	38	6.42 (0.72)	$t\,(86) = 1.263$, $p = 0.210$

† ***Highly significant ($p \leq 0.001$), **significant ($0.001 < p \leq 0.01$), and *weakly significant ($0.01 < p < 0.05$).

months cohort and 5.35 (SD = 1.21) by the 24-months cohort (Fig. 6). The quality of the acoustic environment in TEC was also sustained over the period of two years investigated as indicated by the non-significant t-tests for all variables (Table 3).

3.1.4. Air quality

The occupants working in the building assessed the humidity of the air in the building as providing an indoor environment that was a fair balance between dry and humid conditions during the summer and winter of the first two years of occupation (indicated by mean values close to 4). The freshness of the indoor air was evaluated similarly with mean values around 4 representing a midway point between a fresh and stuffy environment in summer and winter. In both summer and winter throughout the two years of initial occupation the building was considered by the occupants to have a tendency towards being odourless rather than smelly. The air movement in the building was rated as generally still by the occupants during the two years of analysis, particularly during the cold season as assessed by the 12-months cohort (Mean = 2.85, SD = 1.40). There were no significant changes in perceived humidity, freshness, odour or movement of air between the two cohorts as indicated by the non-significant t-tests (Table 3). The air quality overall in TEC was assessed positively by the workers in both summer and winter during the first two years with mean scores greater than 4 (Fig. 7).

3.2. Productivity

The majority of the occupants working in the building stated that the conditions in the building had increased their productivity in the workplace (Fig. 8). An average gain in productivity of 12.98 % was reported by workers in the 12-months cohort and 9.17 % in the 24-months cohort. A non-significant *t*-test result ($t\,(81) = 1.048$, $p = 0.298$) was obtained for the change in productivity between the 12 and 24-months cohorts implying that the increases in productivity observed were also sustained over the first two years of occupation (Table 3).

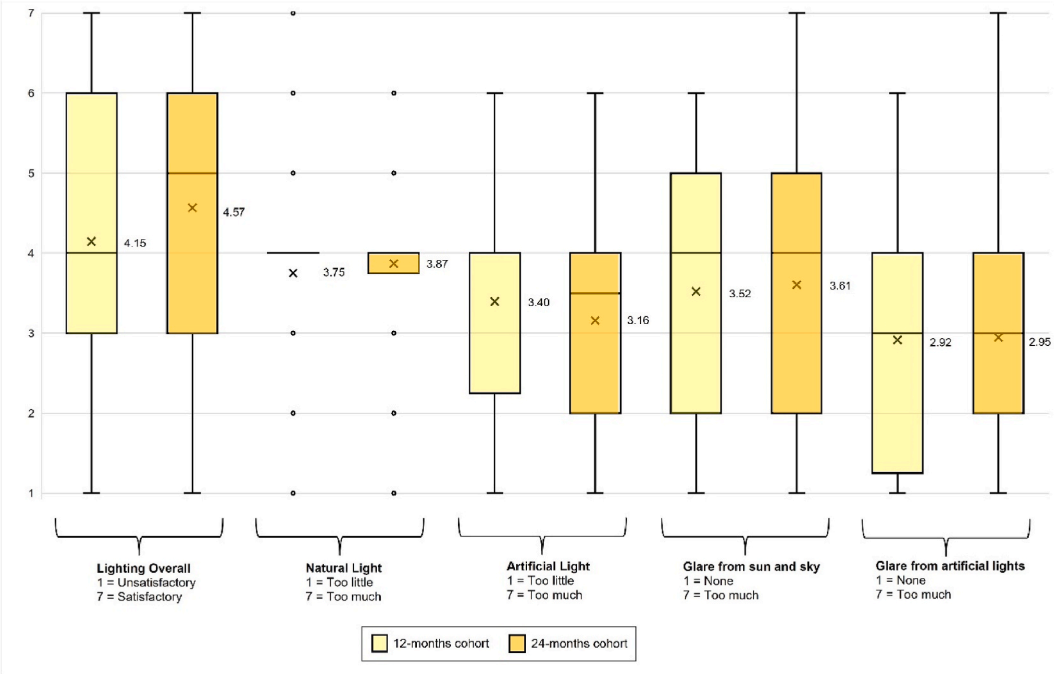

Fig. 5. Natural and artificial lighting.

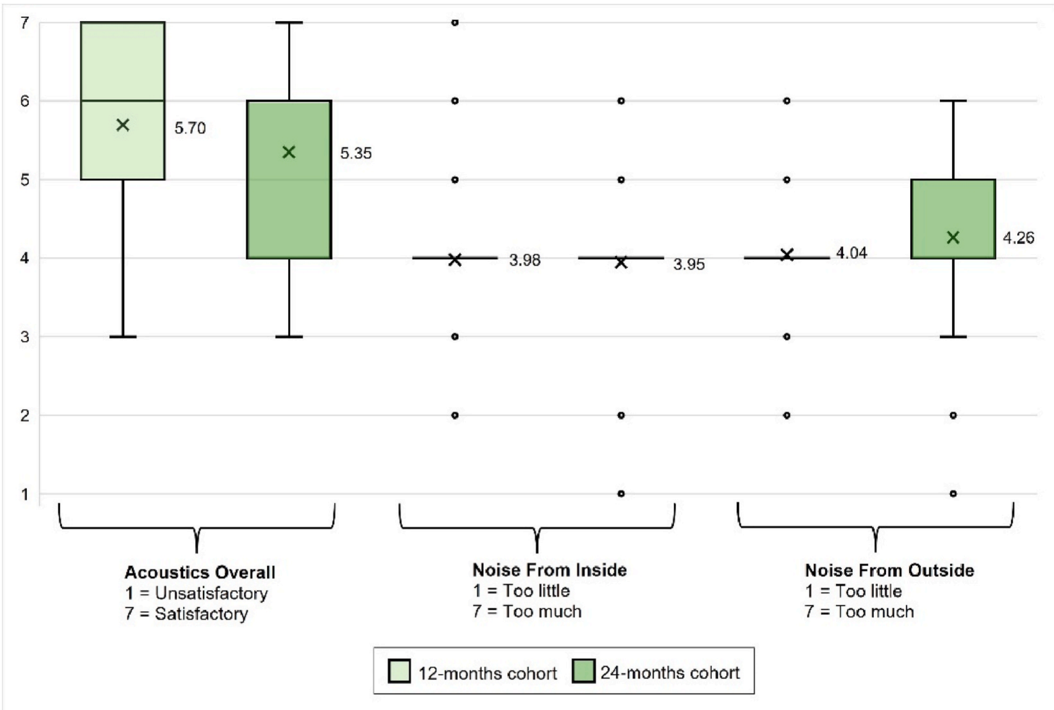

Fig. 6. Acoustics.

3.3. Health and well-being

The occupants working in TEC reported that the building had a positive effect on their overall health and well-being (Fig. 9). A non-significant *t*-test result ($t\,(80) = 1.422, p = 0.159$) was found for the change in perceived health and well-being between the 12-months

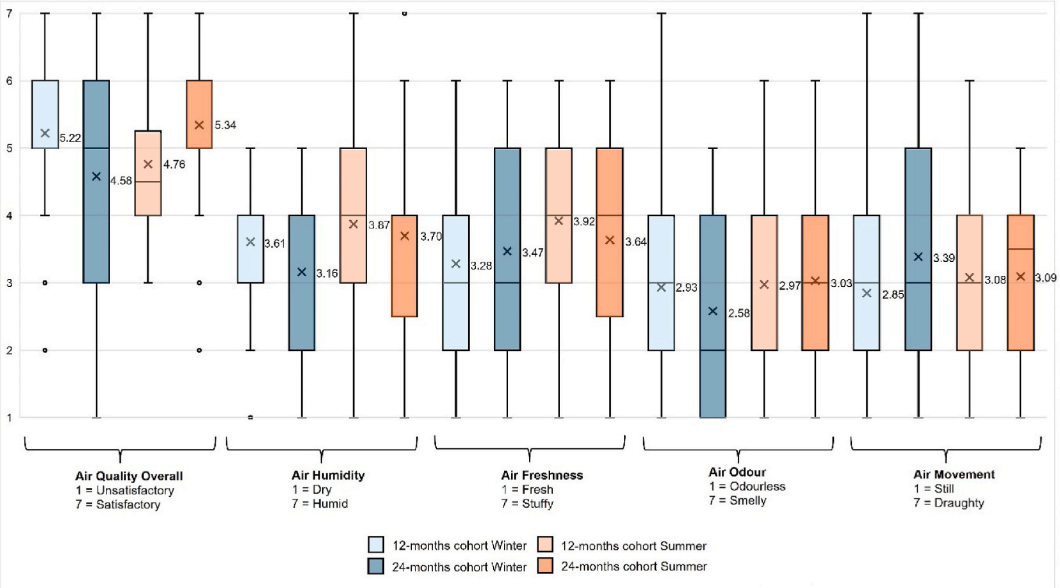

Fig. 7. Air quality in summer and winter.

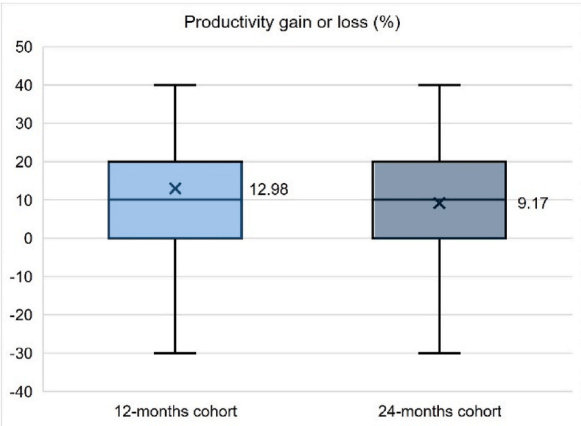

Fig. 8. Productivity of the building's workers.

cohort (Mean = 4.96, SD = 1.31) and 24-months cohort (Mean = 4.57, SD = 1.12) which suggests that the reported health gains have been maintained over the first two years of occupation (Table 3).

3.4. *Overall comfort*

The occupants working in the TEC building evaluated the overall comfort as highly satisfactory with mean scores greater than 5 reported by both the 12-months (Mean = 5.63, SD = 1.02) and 24-months cohorts (Mean = 5.53, SD = 1.16) (Fig. 10). A non-significant *t*-test result (t (84) = 0.419, p = 0.676) indicates that the high levels of overall comfort perceived by the workers in the 12-months cohort were similarly observed by those in the 24-months cohort demonstrating that comfort was sustained over time (Table 3).

3.5. *Building design*

The occupants working in the TEC were highly satisfied with the building's overall design, as well as the image it presented as a whole to visitors (Fig. 11). The average rating of the building's design and image was assessed as greater than 6 (highly satisfactory) by both the 12-months and 24-months cohorts. However, a significant *t*-test (t (86) = 2.649, p = 0.010) indicates that whilst workers in the 24-months cohort remained highly satisfied with the building design, there was a significant reduction in their satisfaction from the

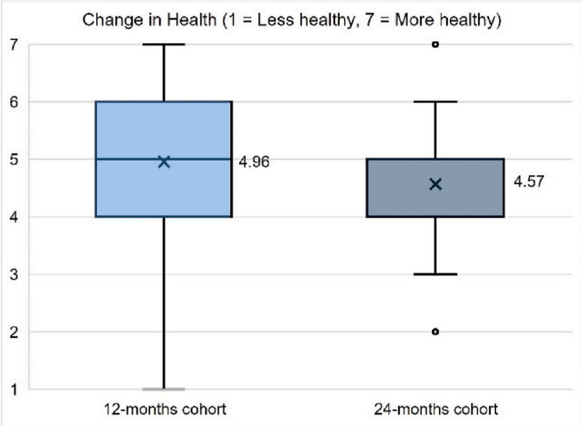

Fig. 9. Health and well-being of the building's workers.

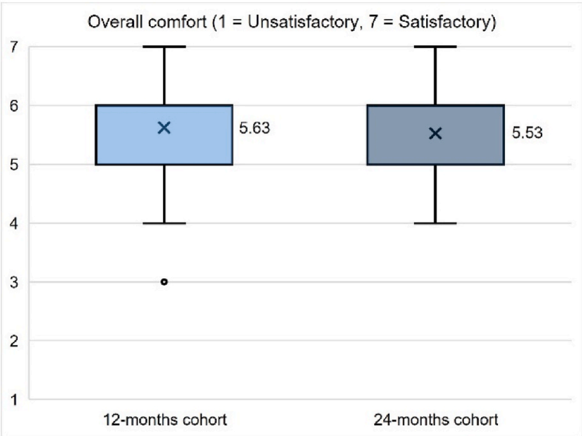

Fig. 10. Overall comfort of the building's workers.

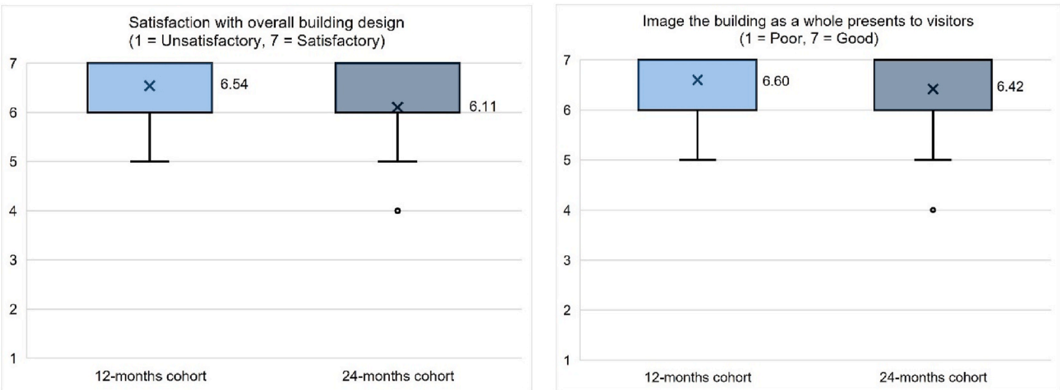

Fig. 11. Satisfaction with the building's design and image.

12-months cohort (Table 3). A non-significant *t*-test ($t(86) = 1.263$, $p = 0.210$) for the image the building presented to visitors between both cohorts suggests that the occupants working in the building believed that the building's design continued to present a highly positive image over the two year period investigated.

4. Discussion

4.1. Satisfaction with the indoor environmental quality

The occupants working in The Enterprise Centre assessed their overall comfort in the building as highly satisfactory over the two year duration of the study. Overall positive levels of satisfaction were also expressed with each individual aspect of the indoor environmental quality, namely the temperature in summer and winter, lighting, acoustics and air quality. These results suggest that the combination of biophilic elements that were incorporated into the building's design have had their expected positive effects on the prevailing indoor environmental conditions. Among the many positive results obtained, of particular note, the use of timber slats and wood wool acoustic panels achieved exceptional control of the indoor noise; solvent-free organic paints and vegetable-based oil coatings as well as the hybrid ventilation system have contributed to a high indoor air quality; and the extensive windows, skylights, clerestory roof and elongated E-shaped building form have provided occupants with suitable levels of natural light, whilst also controlling glare. These results confirm the findings of previous studies that biophilic design aspects, such as the use of natural materials and finishes [56], provision of natural light and ventilation [57,58], etc., can positively alter the indoor environment of buildings for their occupants.

Whilst the workers' satisfaction with the IEQ was generally positive, the thermal environment in TEC was assessed as slightly cool in winter and slightly warm in summer. Some possible reasons for this finding could stem from the building's biophilic design, such as: increased heat losses and gains due to the greater proportion of glazing provided for natural light; natural materials may provide less insulation or thermal mass compared to other non-natural materials like concrete; and an emphasis on passive design rather than mechanical systems to heat and cool the building.

In addition, the artificial lighting in the building was considered slightly less than desired, this result may relate to the building's primary focus on providing natural light to illuminate the indoor visual environment. This may have resulted in an underestimation of the need for artificial lighting, particularly on the overcast and gloomy days, which can be prevalent in the UK climate throughout the year. Also it should be noted that an intentional design decision was not to artificially light the office spaces from the ceiling, instead, built-in over desk lamps were the primary lighting source with only low illuminance LED strips at a high level for background lighting. This finding suggests that the occupants' assessment of the adequacy of artificial light may have been affected by a perceived under illuminance of the wider office space where the direct desk lighting was less effective.

4.2. Effects on productivity and health and well-being

Improving staff productivity in the workplace can have significant economic benefits to companies because 90 % of typical business operating costs relate to staff salaries. It has been estimated that a 10 % increase in staff productivity can realise a 9 % cost saving for business operation [59]. Presenteeism, the act of workers turning up to work but having low productivity and engagement in their work has been estimated to cost UK businesses £100 billion per year in 2024 and in the USA this figure is over $200 billion per year [60].

In this context, the findings reported in this paper that TEC's biophilic design contributed to an increase in productivity amongst its permanent workers is highly significant. Over the two year period investigated, the mean productivity gain was 12.98 % for the 12-months cohort and 9.17 % for the 24-months cohort. These productivity gains are similar to those reported in previous studies which range from 6 to 15 %, such as the study by Nieuwenhuis et al. [38] for office spaces in the UK and Netherlands which were landscaped with plants, who reported a 15 % increase in productivity among workers over a three month period, or Browning and Cooper [61] who described an average 6 % boost in productivity for a range of different occupations where natural elements like greenery and sunlight were incorporated into their workplace. It is particularly noteworthy that an increase in productivity was observed in both years of this study.

Of course, the overall percentage effect of biophilic design on productivity will vary according to the type and extent of biophilic elements used in the building and the work being undertaken. Whilst it is not possible to disentangle the contributions of each biophilic design element used in TEC to the overall productivity gains observed, as described above, it was found that each individual indoor environmental quality aspect investigated was positively assessed by the building's workforce. The notion that the thermal, acoustic, lighting and air quality conditions provided in a workplace can result in reductions or improvements in worker productivity is well established by previous studies [4–6,8,40]. Thus, the increases in productivity observed likely result from the combined effects of the comfortable temperature, lighting and acoustic environments, as well as air quality conditions experienced by the workers, which were achieved through the full range of biophilic elements used in the building.

Earlier studies have established that cultural and individual differences and preferences [61] also play a role in determining the relative impact of distinct biophilic elements on productivity, for example, the use of natural colours has been shown to be more positively associated with worker productivity in India, whereas natural materials were more important in Germany and natural light in China. By implementing a combination of biophilic aspects in TEC, including natural materials and colours, natural light and fresh air, views to outside nature, it would appear the building was able to engage a broad spectrum of workers and in so doing deliver significant productivity gains.

In addition to productivity benefits, the wide range of biophilic elements used in TEC appeared to also have a positive effect on people's perception of their overall health and well-being. The participants stated that they felt more healthy when they were in TEC compared with their experience of using other buildings. A mean of 4.96 and 4.57 for both the 12-months and 24-months cohorts respectively indicated a positive effect (on a 7-point scale, 4 indicated no positive or negative effect on health) on the workers' perceived health in both years. In addition, as indicated by the non-significant *t*-test, the perceived positive health benefits were similar in both years studied. Positive health benefits of nature on human health and well-being are well established by earlier studies [1,2,27], including reduction in stress, faster healing, improved cognition, more positive emotions, etc. Previous research has indicated that well-being can increase up to 15 % when people work in environments with natural elements [61].

It is important to also acknowledge that an employee's health will also affect their productivity, as workers with illness and other health conditions may become absent from work (absenteeism) and as discussed above, those that do attend, may have reduced work rate and performance due to their health issues (presenteeism).

Furthermore, this study provides evidence that biophilic design can benefit people's health, well-being and productivity. However, it should be noted that the positive effects observed for both health and well-being and productivity reduced between the 12-months and 24-months cohorts. This could indicate that the beneficial effects of biophilic elements reduce over time. Data from a single group of occupants working in a biophilic designed building over a longer time duration is required to confirm this. It is also important to state that TEC was a newly completed and occupied building when this study was undertaken, therefore, the biophilic elements were new and part of a consistent design concept. Over time, it could be imagined that issues such as lack of maintenance, for example, reduced natural light due to uncleaned windows; deterioration of the natural materials; inclusion of non-biophilic components; or even changes to the natural outside views due to construction of new buildings or infrastructure, may well come into play and thus reduce the positive effects on people's health, well-being and productivity. Again, such confounding factors warrant further investigation.

4.3. Occupant satisfaction with biophilic design

The results obtained in this study suggest that the use of biophilic design can also have additional positive effects on workers' overall satisfaction with their building as well as their views on the image it presents to others. Previous research has shown that employees that have higher satisfaction with their work environment are also more engaged with their work, company culture and community and this increases their performance and productivity [31–35]. This positive feedback loop appeared to be evident in TEC. Furthermore, the workers in TEC believed the building's biophilic design displayed a desirable work environment to external visitors. Earlier research has indicated that the design of a work place affects a third of people's decisions as to whether they would like to work for a company [61]. The positive image that biophilia presents to external people could therefore play a part in a company's identity when looking to attract or retain staff. Overall these findings should be highly encouraging to future designers considering integrating biophilic design components into their building and workplace designs.

Finally, it is important to note that whilst the overall high level of satisfaction with the building's design amongst its occupants was evident for both years investigated (mean score greater than 6 for both 12 and 24-months cohorts), a significant *t*-test result, indicated that the level of satisfaction of the workers' in the 24-months cohort significantly reduced compared to those in the 12-months cohort. The causes for this decline and any further reductions in satisfaction over time warrant further investigation with a single cohort in a study greater than two years.

5. Conclusions

This paper investigated the effects of a biophilic designed building on the indoor environmental quality, health and well-being, and productivity of its permanent workers. The Enterprise Centre, an exemplary biophilic case study building in the United Kingdom was studied over a period of two years using a repeated cross-sectional study design.

This study makes novel contributions to knowledge in three main ways: first, prior studies have used single-point or short-term evaluations, this study offers a two-year repeated cross-sectional analysis. Second, the study examines the combined effects of multiple biophilic strategies across an entire building, moving beyond the evaluation of isolated interventions that are typical in the existing research. Thirdly, the study generates new evidence on the relationship between biophilic design and occupant health, well-being, and productivity which are lacking in the existing literature.

The key findings of the study are:

- The workers were highly satisfied with the indoor environmental quality in the building. These results suggest that the wide range of biophilic design aspects implemented in the building had positive effects on the full spectrum of thermal, acoustic and lighting environments as well as indoor air quality.
- The workers expressed high levels of satisfaction with the indoor environmental quality and indoor air quality in the building in both years investigated. This implies that biophilic design can have beneficial impacts on the indoor environment.
- The occupants working in the building reported that the building improved their health and well-being. These positive health benefits were evident in both of the years studied.
- Mean productivity gains of 12.98 % were observed for the 12-months cohort and 9.17 % for the 24-months cohort.
- The workers were highly satisfied with the building's biophilic design and believed the design presented a good image to external visitors.

The Enterprise Centre has provided compelling evidence of the value of biophilic design for improving IEQ and health, well-being and productivity of workers. The biophilic strategies used in this case study building could be implemented in other new or retrofitted buildings to achieve similar outcomes.

- This paper has described an extensive range of biophilic strategies and features used in combination and at scale in TEC (Section 2.1) and these could be employed by future building designers to improve thermal comfort, acoustics, lighting, and air quality.
- The research indicates that organisations aiming to improve the health, well-being and productivity of their workforce should consider implementing biophilic strategies and features.
- Evidence of the benefits of biophilic design should encourage developers or building owners to consider incorporating biophilic design into their buildings.
- Workers believed that biophilic design projected a positive image to visitors and reflected a desirable working environment. Organisations should consider using biophilic design to strengthen their buildings' identities and as a strategic asset.

In conclusion, the findings of this study confirm the insights of previous research that biophilic design can improve the indoor environmental quality inside buildings and increase the health, well-being and productivity of building occupants. The biophilic design aesthetic was highly rated by the participants of this study, which indicates that designers should be able to successfully integrate biophilia into future buildings and spaces.

CRediT authorship contribution statement

Rory V. Jones: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Alba Fuertes:** Writing – review & editing, Visualization, Methodology, Investigation, Conceptualization. **Peter A. Bilverstone:** Writing – review & editing, Resources, Investigation, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Professor John French conceived and secured the funding for TEC building and led the project to completion. Without his vision for an ultra-low carbon and biophilic building this research would not have been possible. The biophilic design aspects were conceived during Professor French's earlier Innovation in Crops project.

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Data availability

Data will be made available on request.

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