Notes for readers This paper was written for publication in *Building Research & Information* in 2019. It passed the blind peer-review stage with amendments. These amendments were made. However, one reviewer's comments suggested that the reviewer was aware of the author's identity, and that the review was not necessarily free from bias. *BR&I* offered to obtain a third peer review to which the author readily agreed. However, the third reviewer rejected the paper on two main criteria: 1. That the Building Use Studies occupant survey system was not of the required academic standard, and that 2. The BUS response scale of 1 – 7 was not academically acceptable and should be a -3 to +3 scale, with 0 as the midpoint scale. As a result of this third review *BR&I* rejected the paper despite it meeting the original peer-review requirements.

The modified paper was then intended to be submitted to *BSER&T* as a follow-up to a published paper on the initial results[1] (the winner of the 2018 CIBSE Carter Bronze Medal for best paper published in *BSER&T*), but it was never formally issued for peer review. The author then became busy doing other things. Furthermore, the onset of the Coronavirus pandemic changed occupancy patterns in office buildings. The author considered that the optimum time for a peer-reviewed publication had then passed.

As office working resumed in 2022, the threat of a return to densities last seen in 2016 has returned. The paper is thus being made available to students and other researchers as an open-access research report. Readers are urged to read the initial paper[1] as background to the full reports.

[1] Bunn R, Marjanovic-Halburd L. Comfort signatures: How long-term studies of occupant satisfaction in office buildings reveal on-going performance. *Building Services Engineering Research and Technology.* 2017;38(6):663-690. doi:10.1177/0143624417707668

Longitudinal occupant satisfaction studies and their potential for managing the comfort carrying-capacity of buildings

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ABSTRACT

This paper reports the outputs of research: longitudinal occupant satisfaction case-studies of buildings analysed at a high level of contextual detail. The research involved seven UK buildings, 2307 individual survey responses, and response rates averaging 82%. Study gaps varied between three and 21 years. Self-reported occupant survey scores and free text feedback for 24 comfort and functionality variables were obtained. Statistical differences in the perceptions of building occupants were triangulated with longitudinal changes in the physical and morphological contexts and respondents' free-text feedback to determine whether changes have a measurable effect on comfort and satisfaction. Interim results prompted the theory of building 'comfort signatures': the propensity for occupant surveys to exhibit statistical consistency in occupants' comfort and satisfaction scores unless and until changes in context occur to alter occupants' perceptions. Analysis of the full research dataset led to the theory that a building's distinctive comfort signature, derived from longitudinal occupant perceptions, may be a basis for setting its comfort and satisfaction thresholds for a wide range of comfort and functional variables, termed a building's 'carrying capacity'. The paper suggests that metrics based mainly on occupant comfort perceptions could be the basis for ongoing management of carrying capacity thresholds.

Keywords: Offices; occupant surveys; comfort; perceived productivity; carrying capacity; longitudinal; case studies.

Introduction

New and refurbished non-domestic UK buildings have long been found to under-perform against expectations (Kimpian, Chisholm, & Burman, 2013; Zero Carbon Hub, 2014; Palmer & Armitage, 2014). However, differences in performance are not limited to a building's technical systems. A performance gap can also exist in the form of occupant discomfort and perceptions of working conditions perceived to be unhealthy and unproductive (Leaman & Bordass, 2017).

Occupants of new and refurbished buildings may find conditions contrary to design expectations: variously too hot, too cold, too stuffy, or too noisy (de Croon, Sluiter, Kuijer, and Frings-Dresen, 2005). There may be functional problems with space and storage, and difficulties with controlling internal conditions (Brager, Pailiaga, & de Dear, 2004; Bluyssen, Aries, & van Dommelen, 2011; Frontczak & Wargocki, 2011).

Researchers have long studied buildings and human perceptions of comfort, health and productivity. Seminal research by Strathclyde University's Building Performance Research Unit (BPRU) in the late 1960s analysed the dynamic nature of environments, the human activities within them and the human environmental control interfaces. The BPRU observed that occupants modify their environment in order to change the way it affects them: "Interaction goes on constantly, and it means that it is incomplete to consider an environment without an activity taking place within it or *vice versa*." (Markus, Whyman, Morgan, Whitton, Maver, Canter, and Fleming, 1972).

Markus *et al* found that the flexibility provided in a building's systems may not be taken advantage of in practice, as people learn to live with physical limitations until a threshold of dissatisfaction is reached, at which point occupants may make interventions to improve conditions.

In the intervening decades many generations of researchers have studied occupant comfort, assessed in reviews of the extensive literature (de Dear, Akimoto, Arens, Brager, Candido, Cheong, Li, Nishihara, Sekhar, Tanabe, Toftum, Zhang, and Zhu, 2013). While much comfort-based research focuses on thermal comfort, this paper subscribes to the more general etymology of human comfort, i.e. overall satisfaction and delight with conditions. Furthermore, much comfort research measures occupant comfort at a fixed point in time, with no longitudinal dimension to determine how occupant satisfaction reacts to dynamic conditions in buildings over time.

Longitudinal comfort studies in real-world buildings are similarly uncommon. The significant and influential analyses of occupant comfort and satisfaction in offices have tended to be the large cohort studies, typified by the Building Assessment Survey Evaluation (BASE) research (Apt, Fisk & Daisey, 2000), the US National Institute for Occupational Safety and Health (NIOSH) project (Mendell, Naco, Wilcox & Sieber, 2003), the Swedish Longitudinal Occupational Survey of Health (SLOSH) surveys (Danielsson, Chungkham, Westerlund & Wulff, 2014), and the European Health Optimisation Protocol (HOPE) project (Cox, 2005).

While the databases from these studies have been exploited by generations of researchers, they are notable for possessing little contextual detail beyond categorizing buildings by age and typology. By contrast, detailed case studies of buildings operating in their natural states are relatively rare, thought to be inherently too chaotic and prone to variance for reliable analysis and subsequent generalization. Others contend that case studies can "close in on real life situations and test views directly in relation to phenomena as they unfold in practice" (Flyvbjerg, 2006).

The few published longitudinal studies available tend to be characterised by small sample sizes and/or modest response rates (Brennan, Chugh, & Kline, 2002; Keeling, Clements-Croome & Roesch, 2015). Others are limited to short time-spans and/or have research designs restricted to single-issue topics, such as studying the perceived productivity of workers moving from cellular to open-plan offices (Bergström, Miller & Horneij, 2015).

The paucity of large-sample, context-rich, longitudinal building studies means there is limited knowledge of how occupants in real buildings react to morphological, physical and operational dynamics over time. The primary aim of this research was therefore to determine whether dynamic contextual changes in buildings over long time-frames have a statistically measurable effect on self-reported occupant satisfaction, and whether such measured effects can be shown to possess causal relationships and to what degree of certainty. This aim motivated the longitudinal study of 24 comfort variables in seven non-domestic buildings (some of which included tenancies), with gaps between occupant surveys varying between three and 21 years.

Interim analysis led to the development of what has been termed a building's longitudinal 'comfort signature' (Bunn & Marjanovic-Halburd, 2017). A building's comfort signature is said to be a propensity for the survey scores of a range of comfort variables to sustain a consistent arrangement characteristic over time, unless or until something changes in the survey building to motivate occupants to score conditions differently. *Ergo*, a statistical change in a distribution of comfort scores would need to be attributable to an identifiable contextual cause. Furthermore, a found statistical movement could not be more likely due to random scoring, nor due to variance likely of data distributions derived from loosely-calibrated human perceptions.

The full research dataset of six office buildings (plus tenancies) and one academy are reported in this paper. The paper further explores the robustness of the initial comfort signature concept and explores how longitudinal fluctuations in occupant comfort perceptions may have practical utility in identifying discomfort thresholds. It examines whether such thresholds could be used to identify limits to a building's carrying capacity, i.e. using occupant perceptions to determine the points at which buildings become uncomfortable and potentially less healthy and productive places, thereby warranting interventions to restore comfort conditions.

Initial research questions were simple, open-ended, and largely investigative:

- Are perceptions of occupant satisfaction different between identical surveys applied in the same building conducted many years apart?
- Are differences random, or is there a pattern in the response data that can be explained by influencing factors in the buildings?
- Can reasonable and justifiable associations be made between changes in occupant perceptions of comfort and satisfaction and changes in operational and organisational factors and built morphology?

Background

The longitudinal case-studies were made possible by unusual circumstances. In the 1990s, the advent of UK government-funded, collaborative research into the performance of non-domestic buildings led to four building performance research programmes that provided potential buildings for longitudinal study: the Post-occupancy Review of Buildings and their Engineering (PROBE) project (Ruyssevelt, Bordass, & Bunn, 1995; Leaman & Bordass, 2001), the Carbon Trust's Low Carbon Building Performance project (Carbon Trust, 2011), and the UK Government's £8 million Building Performance Evaluation and £6 million Invest in Innovative Refurbishment research programmes run between 2012-2015 by the Low Impact Buildings Platform of InnovateUK.

These programmes provided candidate buildings for which baseline energy performance and occupant satisfaction data were available. The author enjoyed enduring personal relationships with building owners and occupiers that facilitated repeat study. As the research had been performed in the public domain, it enabled the buildings to be fully described, thereby providing greater detail and clarity of context than would otherwise be possible. All buildings had been analysed using the Building Use Studies (BUS) occupant survey – a key research requirement – to a high level of quality.

Case study selection

A database of 41 buildings (21 schools and 20 offices) were identified as suitable for longitudinal study. The database was passed through a quality filter covering BUS sample sizes, response rates, quality of survey administration, willingness of building owner/occupier to collaborate, and availability and quality of contextual information and historical building data. The filtering reduced the database to around 10 buildings.

Eight buildings were earmarked for longitudinal study and seven finally studied. The key characteristics of the buildings are shown in Table 1 with details of the occupancy surveys in Table 2. All buildings have been coded for consistency and to protect anonymity of tenants.

Table 1: the key characteristics of the seven buildings. Tenancies for Building T are shown in shaded boxes.

Study building	Type	Built	GIA m²	Ventilation type
Pilot building A	Academic office	1994	3130 m²	Mixed-mode (Termodeck) with manual windows
Pilot building B	Single occupier office	2005	7350 m²	Mixed-mode (motorised windows)
Pilot building C	Local authority office	1974 (approx)	1180 m²	Natural, with background mechanical ventilation
Pilot building D	School and offices	2009	10,172 m²	Mechanical, plus openable windows
Building E	Tenanted offices	2006	4852 m²	Natural (manual and locally-controlled motorised windows)
Building F*	Tenanted offices	1990	19,780 m²	Mixed-mode retrofitted to full air-conditioning
Building G	Local authority office	1960s	3000 m²	Mixed-mode (manual and automatic windows)
*Tenancy F1	Wholly open-plan tenanted offices	2008 (refurbished to tenancies)	1100 m²	Mixed-mode retrofitted to full air-conditioning
*Tenancy F2			1124 m²	Mixed-mode retrofitted to full air-conditioning
*Tenancy F3			1700 m²	New office space with full air-conditioning
*Tenancy F4			1630 m²	New office space with full air-conditioning

Table 2: The survey details of the seven buildings. Tenancies for Building T are shown in shaded boxes.

Study building	Survey	Max occupancy	Survey occupancy (est.)	BUS responses	Response rate
Pilot building P	Mid 2012	150	101[a]	100	99%[b]
	June 2015	150	102	73	71%
Pilot building F	March 2013	150 approx	70	64	78%
	May 2015		70	69	98%
Pilot building EA	January 1998	70	70	41	58%
	November 2011	120	N/A	60	N/A
	June 2015	160	100	90	90%
Pilot building HB	November 2006	475	255	242	92%
	May 2015	586[c]	500+	361	66%
Building R	March 2007	300	N/A	109	N/A
	June 2015	262	150	118	80%
Building Q	June 2006	257[d]	N/A	158	62-88%[f]
	July 2010	275	N/A	158	82%
	October 2016	356	249[e]	217	82%
Building T*	June 1995	1300	N/A[g]	119	99%
	June 2016	1136	N/A[h]	411	66%[e]
*Tenancy TA	June 2016	174	122[e]	98	80%[e]
*Tenancy TZ		212	148[e]	119	81%[e]
*Tenancy TC1		120	84[e]	62	74%[e]
*Tenancy TC2		83	58[e]	50	86%[e]

[a]Unverified
[b]Unverified
[c]Actual occupancy could range from 600 to 900
[d]Based on 2007 seating plans
[e]Assuming 70% utilisation
[f]Dependent on desk utilisation
[g]Random sampling carried out on 120 respondents. Total occupancy unrecorded.
[h]Total occupant numbers unknown as one tenant declined to take part. Only four large tenancies studied separately (80% of the 2016 survey sample).

The longitudinal surveys of the seven buildings provided a total population sample of 2307 individual responses. This is modest compared with the 6537 responses over 56 buildings achieved in the EC-Audit project (Bluyssen, De Oliveira Fernandes, Groes, Clausen, Fanger, Valbjørn, Bernhard, & Roulet, 1996) and that of the BASE project involving 4326 responses from 100 buildings (Womble, Girman, Ronca, Axelrad, Brightman, & McCarthy, 1995). However, the averaged response rates from these were 117 and 43 responses per building respectively, compared with the author's averaged rate of 144 responses per survey (Table 2). The author's dataset may therefore be claimed to possess a level of depth and representation the equal of that achieved in the large-scale and oft-cited occupant health and satisfaction studies of the past 30 years.

Of the seven non-domestic buildings ultimately selected for study, two were surveyed three times. Three survey points provided an opportunity to plot longitudinal trends, such as progressive increases in density, rather than merely a change between two points in time.

Research design

The research adhered to the analytic process advanced by Ritchie (Richie, Lewis, Nicholls, & Ormston, 2014, page 276), with the added refinement of multiple iterative feedback loops. The research methodology was thereby a form of grounded theory, informed by the three principles of emergence, theoretical sampling and constant comparison (Walsh, Holton, Bailyn, Fernandez, Levina, & Glaser, 2015).

The research was split into two stages. Pilot studies (the Stage 1 studies) were used to check for patterns in sample population distributions for 24 seasonal and functional comfort variables. Statistical deviations in perception scores were then compared with known, observed, or measured changes in each building's morphological, physical and operating contexts. Findings from the Stage 1 projects were used to improve the research methodology for study of three more office buildings (the Stage 2 studies).

Occupant survey methodology

The requirement to capture occupant satisfaction perceptions longitudinally, over periods of years, dictated the use of the BUS occupant survey. The BUS survey is a three-page, self-completion questionnaire designed to poll occupant satisfaction for a wide range of environmental variables, such as winter and summer temperature, air conditions, acoustics, lighting, and overall comfort.

Functionality variables include satisfaction with space use, meeting rooms and storage. Respondents are also polled on how the building affects their subjective perception of productivity. Background information includes respondent's location in building, and their gender and age band.

Scores are recorded mostly on 7-point semantic differential scales using antonym scale labels (e.g. 'too hot' - 'too cold', or 'unsatisfactory' - 'satisfactory'). Some questions are equipped with free-text boxes for respondents to add more information.

The immediate forerunner of the BUS survey, the Office Environment Survey (OES) was used in the Health Optimisation Protocol for Energy Efficient Buildings (HOPE) project. The later BUS version was a core tool in the aforementioned UK building performance research programmes. At the time of the research the BUS survey was the only system to have been applied systematically on UK non-domestic buildings for over 25 years without major changes. Both the BUS questionnaire and the OES have been tested successfully for reliability and validity (Wilson & Hedge, 1987); (Raw,1995); (Parkinson, Reid, McKerrow, & Wright, 2017).

The paper-based questionnaires were handed-out to building occupants and retrieved on a single day. The research relied on paper surveys in order to get the highest response rates as well as additional insights from the building visit itself.

Two questions were added to the BUS questionnaire motivated by findings from previous research: controls usability (Frontczak & Wargocki, 2011) and perceptions of occupant density (Keeling *et al*, 2015). The population sample scores were triangulated with the contextual evidence and respondents' free-text feedback to identify explanatory reasons for longitudinal statistical differences.

Matched or related-pair scoring was not possible due to long gaps between BUS surveys and the natural turnover of staff in the occupying organisations. Generalization was confined to identifying consistent patterns between buildings for characteristics that could be analysed universally, such as the effect of density on occupant satisfaction with noise.

Context mapping

As the research was heavily dependent on the longitudinal mapping of context, it was vital to analyse the physical qualities of each building to a high level of detail.

Little published research was available to inform a consistent way of mapping a building's physical, morphological and operational contexts. It was vital to have a thorough and robust method of capturing context in order to achieve consistent comparison with data from the BUS occupant survey. The process began by developing a theory of context.

The theory of context centred on the idea that contexts in buildings are nested: that a building can be decomposed spatially and typologically into smaller contexts that layer at primary, secondary and tertiary levels (Figure 1).

The primary context was the entire building, with a secondary context a separate floor, or an otherwise discrete or bounded space (i.e. separately occupied). A tertiary context may be disaggregation of window

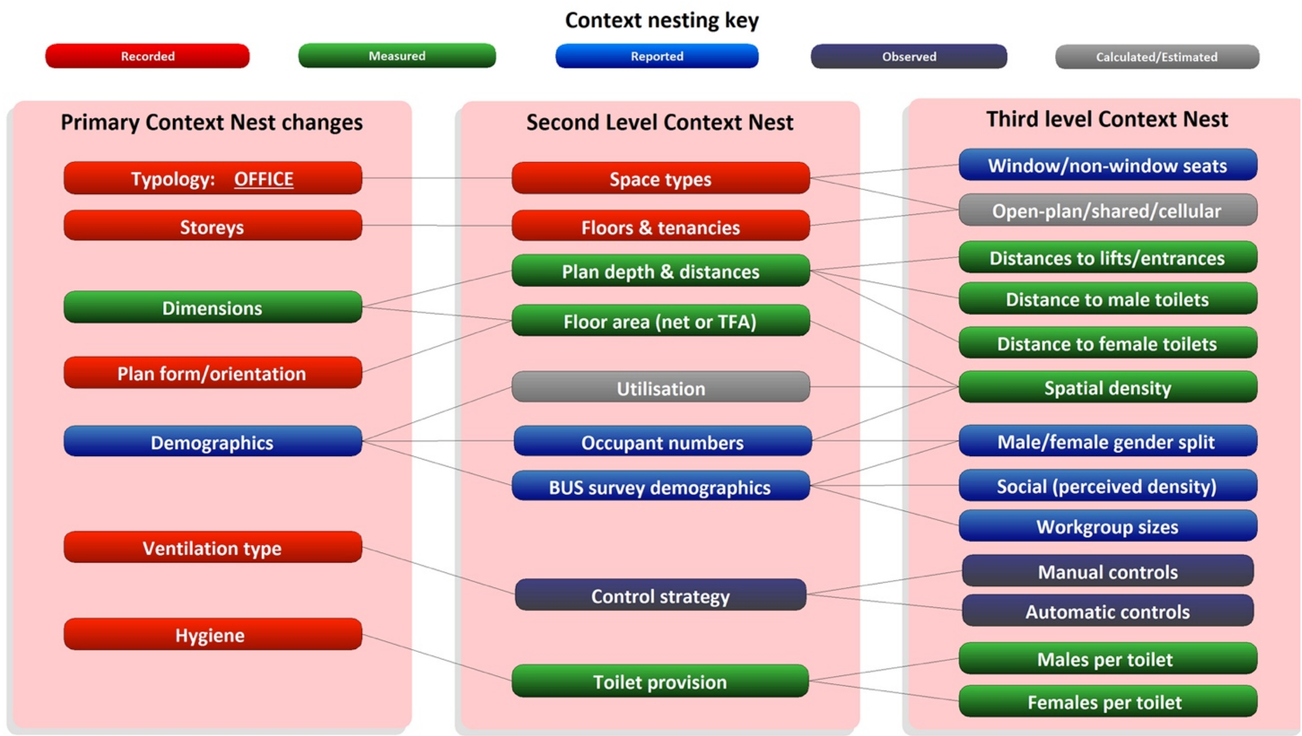


Figure 1: The theory of context comprised five sources of information and data over three nested levels.

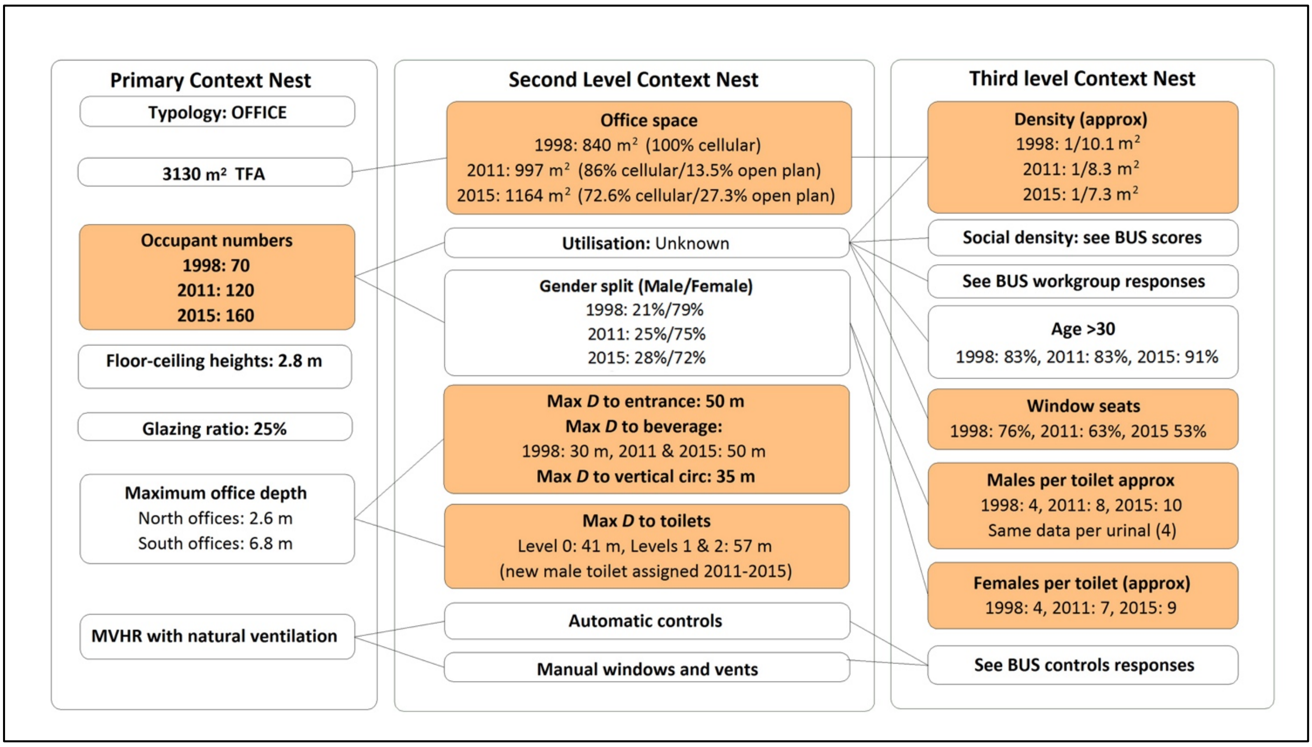


Figure 2: The context nest for Building A, with longitudinal changes highlighted.

and non-window seating locations, or cellular, team and open-plan office environments.

The degree of resolution in the context nests was largely dictated by the location-related questions in the BUS questionnaire. There was little point in creating a nested context for which there was no comparative survey sample. However, the range of questions in BUS enabled the nesting of contexts to a level where there were no indistinct areas or missing sub-samples. It was possible to disaggregate population samples by age, gender, floor, spatial location (department), and workgroup size when the separated samples sizes were large enough to justify statistical analysis (i.e. samples greater than 30 respondents, and/or above 60% of the total staff allocation).

Figure 1 illustrates that contextual data and information was obtained from up to five sources. The level of detail for each case study was dependent on the availability and accessibility of recorded and contemporary information.

For reasons of space it is not practicable to show all context maps for the individual buildings and zones. Figure 2 illustrates a typical context map of a building with highlighted boxes recording where changes had occurred.

Statistical tests
Data analysis comprised three approaches:

- Comparison of longitudinal, building-specific occupant satisfaction sample distributions using non-parametric statistical tests appropriate for non-normal and unpaired distributions
- Qualitative analysis of occupant free-text comments
- Comparison of quantitative and qualitative data with descriptive statistics derived from the context nest characteristics.

Statistical differences were tested using the *t*-test within the Mann-Whitney U-test. This determined the degree of equality between two sample distributions (Mann & Whitney, 1947). The Mann-Whitney test calculates the number of wins in a pair-wise contest. It is thus a slightly tougher *t*-test than the classic student's *t*-test.

The researcher opted for caution to reduce the likelihood of Type 1 or Type 2 statistical errors. Only results from two-tailed tests were used, as samples could move longitudinally in either direction. This self-imposed constraint also helped neutralise researcher bias.

Particular care was taken when reporting statistical changes in perception scores over time. While statistical differences are reported at the classic 95% confidence level ($\rho \leq 0.05$), it is fully acknowledged that $\rho \leq 0.05$ is a purely arbitrary statistical threshold, often applied universally without recognition of the type of data, their source and intrinsic properties, sample sizes, and distribution characteristics.

The researcher did not, therefore, feel constrained by the arbitrary 95% threshold. Samples that exhibited longitudinal movement around a 90% confidence threshold were also considered indicative of a shift in occupant perceptions that may be linked to a contextual cause (Salkind, 2008 p163). Hence while the statistical analysis erred on the side of caution, with only *t*-test results at or above the 95% confidence threshold being recorded as statistically different, it is nonetheless suggested that statistical movements between 80-90% may be insightful and should therefore never be completely eliminated from statistical assessments.

It is also important to recognize that sample distributions generated from occupant surveys are often not Gaussian. They may exhibit skew, bi-modality, or other non-normal characteristics for a variety of contextual reasons. Perception scores for air conditions can be influenced by respondents' proximity to openable windows or ventilation openings. Differences over time may be also amplified or suppressed by shifts in a gender or age balance. Longitudinal changes for age and gender balance were therefore checked before any longitudinal statistical differences were attributed to contextual causes.

Graphics and reporting conventions
The BUS standard (i.e. industry-adopted) charts are used in the results section to summarise the longitudinal statistics for each study building. Due to the large number of building surveys (14 individual surveys, plus disaggregation by tenancy and floor level for each survey year) it is not practicable to show the data distributions for all 24 comfort and satisfaction variables for all buildings and zones. For the purposes of this paper, the results for each building and tenancy have been reduced from 24 variables and incorporated into summary charts for 13 key variables.

While some graphics in this paper are necessarily reproduced in greyscale most are in colour. Note that colour-coding in standard BUS summary charts indicate mean scores that statistically above, below or the same as scale midpoint. In this paper the colour-coding only differentiates scores for different survey years.

The population sample mean scores are grouped into four categories: seasonal, functional, user control, and outcomes. Variables that have a seasonal component are temperature, air conditions, and natural light. Functional variables, such as space-use effectiveness, were grouped with other variables that are partly a product of functional components (e.g. noise). User control variables cover respondents' assessment of their personal levels of control over heating, cooling, ventilation and lighting, and control of noise sources.

The confidence limits to the sample means are not shown. Instead, the statistical movement of the underlying distributions, at $\rho \leq 0.05$, are shown as arrows on the right axes. Note that for buildings with three BUS surveys, some variables initially improved then declined. This characteristic is indicated by overlain arrows.

BUS benchmark references are shown as vertical hashes. The longer the hash, the more recent the benchmark reference. BUS benchmarks are mean scores for a concurrent rolling database of 50 buildings. Although the benchmarks played no part in the longitudinal statistical assessments, they have value in indicating how far each mean comfort score was from the averaged score of 50 similar buildings at the time.

Free-text responses

Analysis of respondents' free-text responses followed a methodology originated by Baird (Baird & Dykes, 2012) and developed by Burman (Burman, 2016). The methodology involves subjectively ranking comments as either negative or positive based on key words and phrases (e.g. 'too hot', or 'very noisy'). Neutral or mildly critical comments (e.g. 'slightly hot', or 'a bit noisy') were classified as 'balanced'. The percentages of each comment in each category were calculated, with the percentages of balanced/critical comments calculated separately but reported alongside the negative percentages (Figure 3).

Space limitations preclude reproduction of all charts for all buildings. Figure 3 shows a typical example (Building A). The percentage bands do not have particular meaning attached to them. However, it was found that comfort variables with poor statistical scores tended to generate a combination of negative and balanced comments (i.e. critical but not wholly damning) by 40% or more respondents.

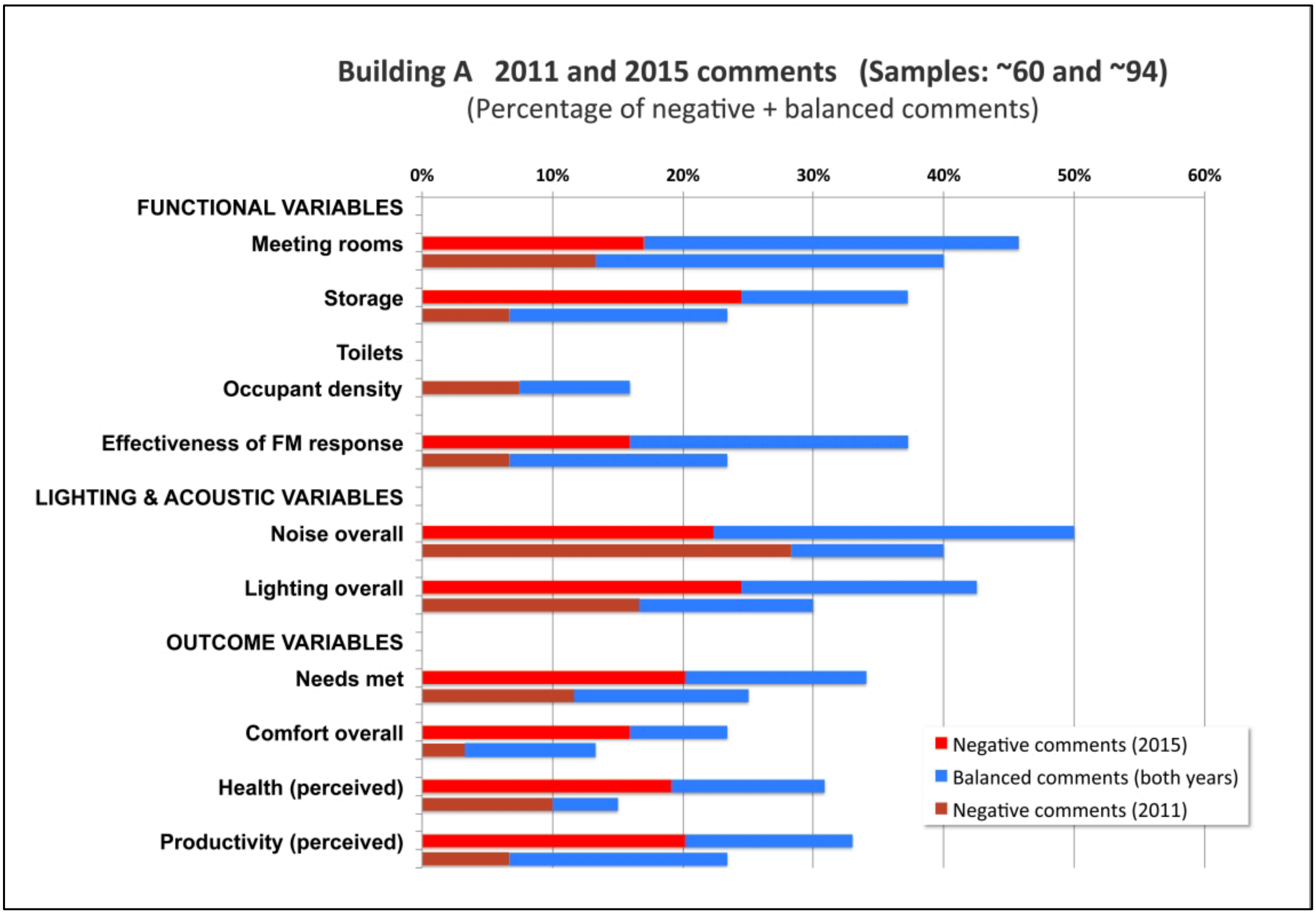


Figure 3: An example of negative and balanced (i.e. critical) comments for two survey years. Percentages calculated as the percentage of those comments against all survey respondents (including 'no commenters').

Severe cases of discomfort tended to generate negative and balanced comments from 50-60% of respondents. However, as the percentages differed building by building, and comfort factor by comfort factor, it is considered misleading to generalize about percentages. True insight comes from reading what respondents say than from distillation into categorized percentages.

Stage 1 pilot studies

Table 1 lists the four pilot studies along with the Stage 2 studies. Table 2 lists the dates of each survey, the sample sizes and the response rates.

Building A

Building A is a four-storey 3250 m^2 university teaching and administration building constructed in 1995. The building featured an early adoption of the Swedish Termodeck mechanically-ventilated structural floor-slab system, designed to provide year-round tempering of fresh air with high efficiency heat recovery (Winwood, 1996). Its longterm performance was subsequently analysed in January 1998 within the PROBE research project (Standeven, Cohen, Bordass, & Leaman, 1998), again in November 2011 (Bordass, 2012; Bunn, 2012), and in June 2015 for the research project.

The building's wholly cellular and shared office spaces – on the north and south facing sides of the building – were augmented by creation of open-plan spaces in stages before and after the 2011 BUS survey (Figure 4). This was associated with a doubling of the building's population between 1998 and 2015. All changes were captured in context nests, and the resulting densities calculated.

Figure 4: High-density open-plan offices created in Building A.

Building B

First occupied in 2006, Building B is a 7350 m2 two-storey, deep-plan building on a trapezoidal footprint (Bunn, 2007). The wholly open-plan building was constructed on a north-south axis with the longest facade facing south. The envelope is a mixture of aluminium curtain walling, with a covered walkway and heavy brise-soleil on the south elevation. The multi-pitched roof is regularly punctuated with mostly north-facing rooflights. There are two large glazed courtyards and an atrium with cafeteria. Nine internal lightwells break up the second floor mezzanine. The pitched floor-to ceiling heights vary between 2.5 m to 5.4 m (Figure 5).

The building is predominately naturally-ventilated with some mechanical ventilation and heat recovery for winter operation. A design objective to reduce energy consumption involved the relaxation of summer and winter thermal set-points.

Figure 5: The wholly open-plan offices of Building B.

Building C

Building C is an 1180 m^2 (treated floor area), two-storey, naturally-ventilated office building constructed around 1974. It is rectilinear and orientated south-east – north-west. It has a flat concrete roof penetrated by some clerestory toplights. Offices on both floors tend to be shared or open-plan, with some cellular offices on the first floor (Figure 6).

The building became available for (short-term) longitudinal study due to the prototype testing of an innovative form of external insulation with a ventilated cavity (Figure 7). Research revealed the building to be suffering overheating prior to the retrofit, largely due to unobstructed solar gain and poor ventilation and air movement.

Figure 6: The open-plan offices in Building C.

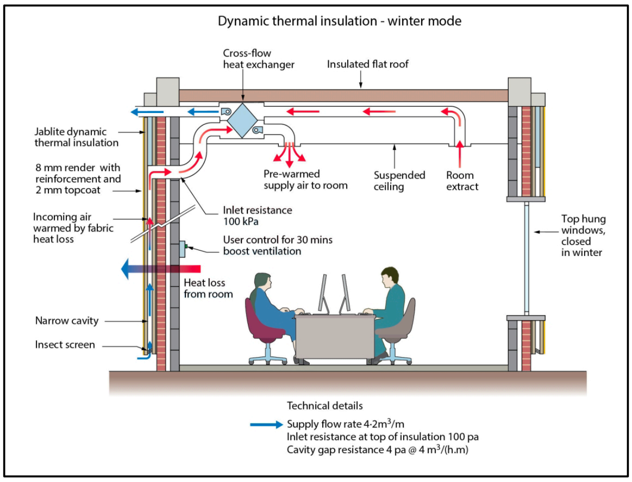


Figure 7: The dynamic external insulation retrofitted to Building C.

In one office, desk fans were permanently fixed to the internal walls. The south-facing windows open out to a refuse-recycling centre. A lorry weighbridge is immediately below the first-floor windows. Both features compromise occupants' attempts to adequately ventilate the south-facing offices. Although opening clerestory toplights had been added some years previously, many Teleflex manual window-winders became hidden behind shelving and therefore unusable.

The BUS survey was used to measure occupant satisfaction prior to the retrofit and again a year after the refurbishment works completed.

Building D

Building D is a secondary school of 10,172 m^2 (Figure 8). Occupied in June 2009, the school is spread over a campus of 12 interconnected two and three-storey steel-framed buildings around an internal courtyard (Kimpian, Chisholm & Burman, 2015).

Figure 8: The open-plan nature of the teaching spaces in Building D.

The buildings are of mixed-mode ventilation, with mechanical ventilation via earth tubes that deliver fresh air through low-level supply terminals. Double-height internal breakout spaces form part of the ventilation route for the perimeter classrooms. Passive stack-ventilation vents vitiate air through high-level operable vents. The majority of perimeter classrooms are provided with single-sided opening windows.

Building P is the only non-office building in the dataset. It was selected for the depth of information available, the quality of the BUS survey, and known changes and improvements that had been carried out in the building as a consequence of the first BUS survey. The building also has some administrative offices that justified its inclusion.

Buildings E, F and G formed the second stage of research.

Stage 2 studies

Table 2 lists the three Stage 2 studies. The Stage 2 studies benefitted from enhancements to the survey technique and minor refinements to the BUS survey. The Stage 2 buildings were generally larger and more complex than the Stage 1 studies. Table 2 lists the dates of each survey, the sample sizes and the response rates.

Building E

Building E was constructed in 2005 as a 4852 m^2, narrow-plan, two-storey building. (Bunn, 2007). The largely timber-framed building is cruciform in plan, with a double-height glazed circulation space running east-west. A 600 mm-thick rammed-earth wall (a by-product of the basement excavation) runs almost the building's entire East-West axis.

The building was designed to house around 500 tenants. The building has a wide range of office types: single-occupant cellular offices, shared offices, and both small and large-scale open-plan offices (Figure 9).

Figure 9: Low-density open-plan offices in Building E.

Building E can be categorised as an advanced naturally-ventilated building, with a mix of single-sided ventilation for cellular offices and cross-ventilation for deeper plan offices. Cross and stack ventilation to the 13 m-deep office spaces is aided by motorised clerestory windows that open to the atrium. Windows are a mix of manually openable windows and side vents. The latter have integral screens to enable background insect-free ventilation and night purging.

Figure 10: Building F open-plan offices located beneath an atrium in 2015, (the open perimeters of which were sealed with glazing in the 2008 refurbishment).

Building F

Building F is a 17,565 m^2, extreme deep-plan office constructed in 1991 over three storeys (Figure 10).

The massive building was defined at the time as a groundscraper, an apt term for a building with open-plan offices spanning up to 120 m. (Corcoran, 1993). The coffered slabs traverse a 13.5 m structural grid, with a floor-to-rib height of 3.62 m and a maximum floor to coffer height of 4.25 m.

In 1991 the two main office floors were penetrated on all floors by three, 14 m diameter circular atriums, each topped by a triodetic dome. All atriums were open-sided so that office floors were effectively a single volume. In 1991 the 3560 m^2 third floor was a staff restaurant.

The envelope on the first two floors is formed of a double-skin facade, with the outer weather screen of clear glass and an inner skin of double-glazed, sash windows. The ventilation was designed to be mixed-mode, with the openable sash windows in the inner façade supplementing mechanical ventilation.

The wholly open-plan building was originally the headquarters of a large insurance company. It was remodelled into separate tenancies in 2008, reducing the floor depths from 120 m to around 27 m (max). At the same time the atriums were glazed-in around their floor-plate perimeters. As the retrofit involved full air-conditioning, the perimeter sash windows in the double-skin facade were locked closed on all elevations. Control of ventilation was thereby removed from the occupants. The building's performance was analysed as part of the PROBE project (Bordass W & Leaman A, 1995).

Two large tenancies were selected for longitudinal study in 2016 (coded F1 and F2). Two other tenancies (coded F3 and F4) are located in two office areas created in the former 3565 m^2 restaurant. The internal morphology of the new tenancies is very different to the lower office floors. Although occupant satisfaction could not be analysed longitudinally, occupant responses to the 2016 survey provided a basis for checking whether the comfort signatures were different to those of the original lower floors.

Building G

Building G is a concrete-framed, three-storey office building constructed in the mid-1960s. The narrow-plan building forms one side of a rectangular site, with the west elevation opening on to an internal courtyard.

In 2007 the building was stripped back to the shell and core. Its largely cellular offices were extensively remodelled to provide four naturally-ventilated office floors totalling around 3000 m^2. While the building's orientation, external dimensions, massing, and service core zones remained the same, most other morphological features such as glazing ratios, floor-to-ceiling heights and environmental systems were changed.

The refurbishment focused heavily on improving the internal environmental conditions. The original suspended ceilings were removed to expose the building's concrete structure (Figure 11). This unlocked the building's thermal capacity, enabling it to moderate internal temperatures. A mixed-mode approach to ventilation was adopted. Openable windows (manual and motorised) were supported by a mechanical ventilation system to avoid the need to open windows in winter.

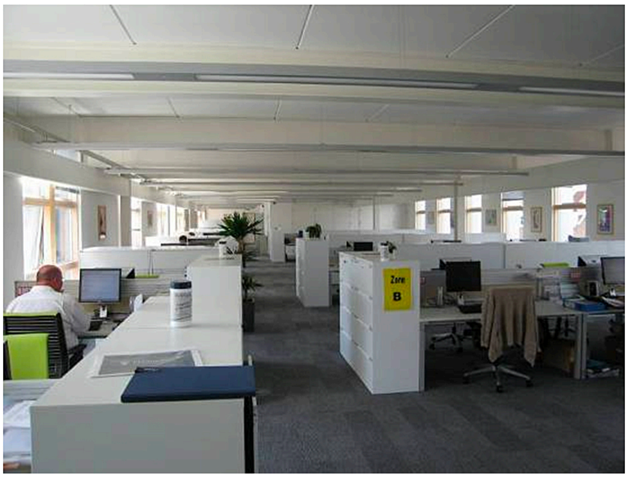


Figure 11: The open-plan offices of Building G in 2010 prior to occupation.

Three BUS surveys were performed: prior to the refurbishment, two years after the refurbishment, and in 2016.

Results: Stage 1 studies

The results charts for each Stage 1 study show mean scores for the 13 summary variables for each building over time. A typical example of all scores and statistical tests for all 24 comfort variables, for one building, is illustrated in Table 3 (*overleaf*). The example reports survey distributions, sample sizes, mean scores, sample variance, and p values. Statistical improvements or declines over time are shown as filled arrows.

Perception scores for Building A were disaggregated by office space type (open-plan versus cellular and shared offices). For Building B, the two BUS surveys were disaggregated longitudinally by department where comparative departmental samples could be identified with certainty from contemporary floor plans. Any change in occupant satisfaction could then be analysed longitudinally against local changes in spatial and social densities.

The longitudinal performance of both buildings showed that some comfort indices had moved statistically at $P \leq 0.05$. For Building A, movement could be linked to physical changes in the building made both before and after 2011. Primarily these changes were a 13.5% shift to open-plan offices in 2008 prior to the 2011 survey. This rose further to 27.3% prior to the 2015 survey. By 2015 the open-plan and large shared offices housed nearly 50% of the survey response population.

Figure 12 shows the mean scores for the survey population samples from Building A. The colour-coding used for the three surveys is shown underneath the chart: cyan dots for 1998, blue dots for 2011, and black dots for 2015.

The sample scores had declined in both 2011 and 2015 compared to 1998. By 2015, mean scores for three of the key comfort variables – summer temperature, natural light and perceived health – had declined below scale midpoint.

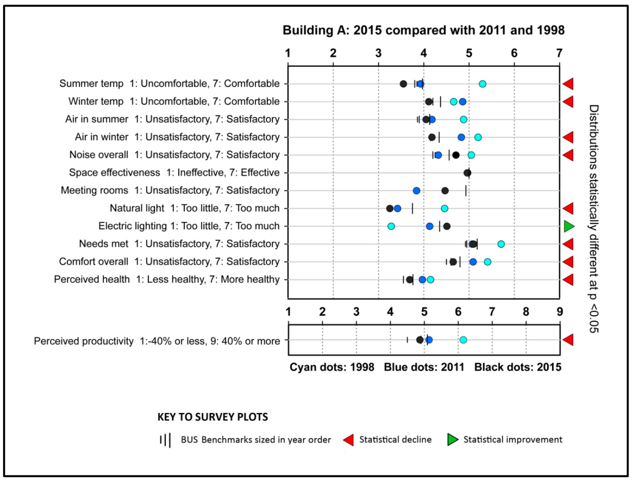


Figure 12: The summary variable scores for Building A. Includes the key style for all other summary charts.

Triangulation of the longitudinal survey data with changes in physical context identified the factors contributing to the statistical movements. The doubling of occupants between 1998 and 2015, along with the shift to open-plan working for half

Table 3: A typical distribution of sample sizes, mean scores and variance for two longitudinal surveys.

Context	Comfort variable	2006 Sample (*n*)	2006 Mean score	2006 Sample variance	2015 Sample (*n*)	2015 Mean score	2015 Sample variance	U-Test for statistical difference $p = <0.05$	Statistically different	Statistical change[1] ↑ Improved ↓ Declined	Link to context evidence
Seasonal	***Summer temperature***	202	3.58	3.03	306	4.19	2.46	<0.0001	Y	↑	
	Summer too hot/too cold[2]	195	3.08	1.97	304	3.51	1.30	<0.0001	Y	↑	
	Winter temperature	228	4.39	2.54	328	3.80	2.67	<0.0001	Y	↓	
	Winter too hot/too cold[2]	209	4.59	1.36	325	5.08	1.59	<0.0001	Y	↓	
	Conditions in winter	230	4.47	2.56	328	3.98	2.11	0.0003	Y	↓	
	Conditions in summer	196	3.88	2.81	306	4.16	1.84	0.0274	Y	↑	
	Natural light[3]	238	3.99	1.42	355	4.15	1.14	0.0611	Y	↑	
	Natural glare[4]	238	3.30	2.64	355	3.51	2.59	0.1097		=	
Functional	*Cleaning*	241	5.06	2.46	359	5.21	2.17	0.2866		=	
	Meeting rooms	229	5.02	1.70	347	3.34	2.68	<0.0001	Y	↓	
	Storage	227	4.13	2.98	349	3.87	2.98	0.0950		↓	
	Space use	238	5.25	1.56	355	4.70	2.06	<0.0001	Y	↓	
	Electric lighting[3]	236	3.86	0.93	352	4.09	0.75	0.0034		↑	
	Noise overall	236	4.13	2.95	355	4.14	2.57	0.9861		=	
	Density (perceived)[5]	-	-	-	314	4.88	1.62	-	-	-	-
User control	***Heating***	235	2.10	1.55	315	1.28	0.71	<0.0001	Y	↓	
	Cooling	232	2.43	2.15	315	1.51	1.28	<0.0001	Y	↓	
	Ventilation	235	3.01	2.79	314	1.77	2.13	<0.0001	Y	↓	
	Lighting	236	2.44	2.68	314	1.76	1.80	<0.0001	Y	↓	
	Noise	235	1.74	1.32	315	1.35	0.71	<0.0001	Y	↓	
Outcome	*Needs met*	239	5.38	1.47	354	5.31	1.64	0.7076		=	
	Comfort overall	237	4.99	1.87	354	4.75	1.73	0.0322	Y	↓	
	Health (perceived)	236	4.16	1.42	354	3.71	1.43	<0.0001	Y	↓	
	Productivity (perceived)	220	5.02	2.36	343	4.80	2.46	0.0279	Y	↓	

Notes

[1] Coloured arrows denote a statistical change at *p* 0.05 showing whether perceptions of a satisfaction variable have improved or declined longitudinally. Black arrows denote the movement of a variable that may be insightful even if a movement is not statistically different. Readers should always note the scale labels.

[2] Scale labels are 1: Too hot, 7: Too cold

[3] Scale labels are 1: Too little, 7: Too much

[4] Scale labels are 1: None, 7: Too much

[5] Scale labels are 1: Too few, 7: Too many (4: About right)

the building's population, led to an increase in density from one person/10.1 m^2 to an average one person/7.3 m^2. This is tighter than industry norms quoted by the British Council for Offices (BCO, 2013). Furthermore, in the largest (165.6 m^2) open-plan office occupied by 32 staff, spatial density was calculated at one person/5.1 m^2 at full utilization.

Evidence of discomfort in the open-plan areas was observed due to rows of desks placed at immediate right angles to the windows. Compared with the cellular offices, where desks could be located at the occupant's discretion, staff resorted to *ad hoc* methods of alleviating glare discomfort using sheet cardboard and other objects.

To determine whether the shift to open-plan offices had contributed to a statistical decline in occupant satisfaction, sample distributions from cellular offices in 1998 (n = ~41 depending on the BUS question) were compared with the 2015 sample distributions for cellular offices (n = ~46). The means of the distributions for open-plan and cellular offices in Figure 13 illustrates the extent of the decline in satisfaction for conditions in the open-plan offices.

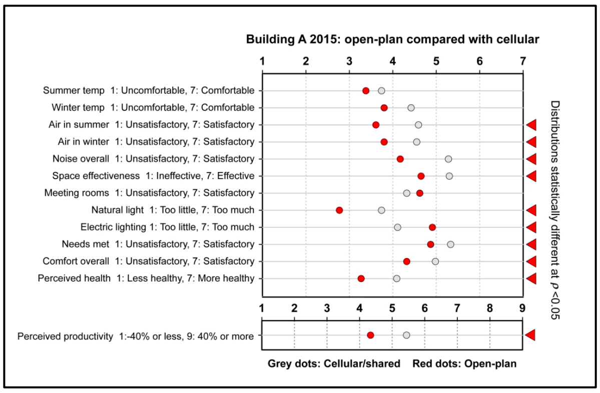


Figure 13: The summary variable scores for open-plan versus cellular offices in Building A.

Scores for temperature in summer, natural lighting and electric lighting were statistically lower in 2015, suggesting that declines in perception for those factors were independent of office type. All other statistical declines could therefore be reasonably attributed to the progressive shift to open-plan offices.

Statistical declines in scores for control over environment are shown in Figure 14. The declines are commensurate with loss of individual control in open-plan areas relative to the cellular offices. While loss of individual control is not necessarily negative, it is more likely to be retrograde where respondents have reported a (statistical) discomfort with seasonal environmental parameters, such as temperature and air quality, that staff in cellular offices may be able to alleviate by using their local controls.

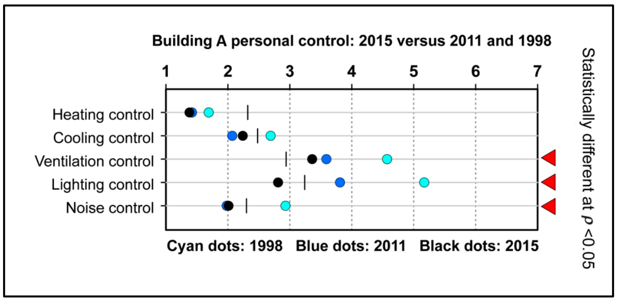


Figure 14: Building A scores for control over environment.

Triangulation of scores with negative and balanced free-text comments for Building A show the percentage increases for 2015 over 2011 for all variables. This finding reinforces the analysis for statistical declines in respondents' satisfaction scores.

Summary longitudinal results for Building B are shown in Figure 15.

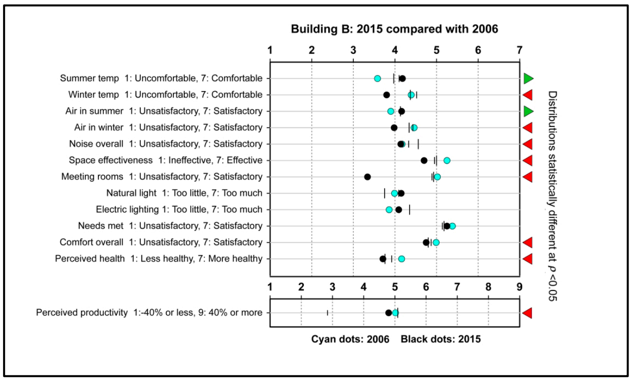


Figure 15: The summary variable scores for Building B.

The satisfaction scores in 2015 had declined for seven comfort factors. Scores for meeting rooms had declined at $\rho = \leq 0001$ suggesting a major fall in satisfaction. Although this statistical decline could not initially be linked to physical changes in the building, investigation quickly identified chronic problems with the meeting room booking system. The problems led to room unavailability, and motivated staff to hold their meetings in the café area. The knock-on effect was a conflict with staff using the café for relaxation and lunch breaks.
A context-related comfort signature was less evident at building B for many comfort factors. Therefore physical, morphological and operational evidence

was sought to determine whether movements in satisfaction scores were a product of normal variance in occupant perceptions or due to some other cause not captured in the context map.

The greatest change in the building was the occupancy levels. The building was designed with 420 workstations. This rose to 475 at the time of occupancy. By 2015 the fixed desk allocation had risen to 586, including 34 nominated hot desks. It was also reported that 900 people could conceivably work in the building at any one time. Swipe-card entry records revealed that occupancy averaged 650 mid-week.

One meeting room had been appropriated as a quasi-cellular office, and some staff reported working in the atrium. Average density in 2006 was one person/14 m^2. By 2015 some departments were working at one person/4.7 m^2. The context-mapping approach identified that persons per unisex toilet cubicle had also increased between 48-54 persons per cubicle, well in excess of the *British Standard* design guidelines prevailing in 2006 (BSI, 2006).

The staff complement for one department, whose boundaries had not changed since 2006, had risen from 68 to 128 by 2015. The increase had partly been achieved by fitting a third person between two desks, with the person straddling the adjacent legs of the desks. This policy not only increased spatial density but also social density.

Fixed departmental boundaries in Building B enabled the 2006 and 2015 BUS survey samples to be disaggregated to determine whether the longitudinal movements in comfort scores were density-related. Although the disaggregated departmental sample did not show statistical changes for seasonal variables, a statistical decline in satisfaction with space-use effectiveness matched the changes in density.

The outcome variables of perceived overall comfort, health and productivity in 2015 had all fallen statistically compared with the 2006 sample. However, perceived comfort was still above scale midpoint, suggesting that while conditions in the building had declined palpably, the decline in performance outcomes had not become critical.

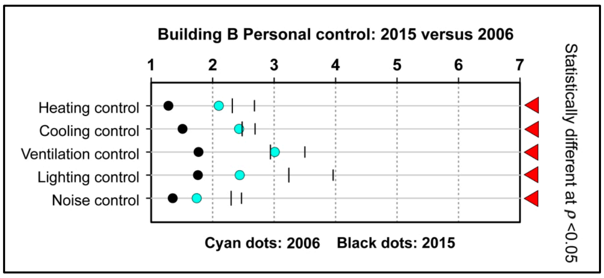


Figure 16: Building B scores for control over environment.

As staff in the open-plan building had found it difficult to reach consensus over vent positions, the original local control of motorized vents and windows was automated and centralized. Changes in physical context were reflected in survey responses for changes in perceived control: all five variables had declined statistically at $p \leq 0001$, the greatest change being for control over ventilation (Figure 16). The change for control over noise is thought likely to be linked to the great increase in social density.

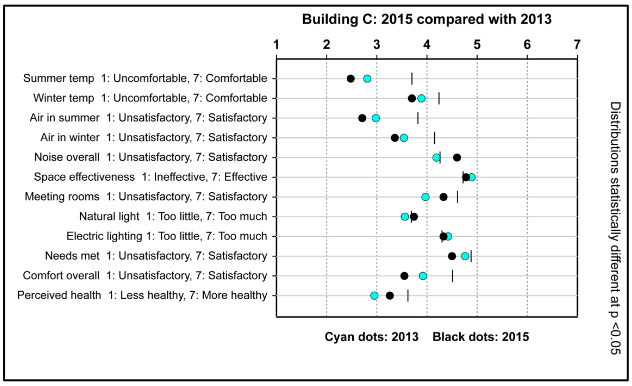


Figure 17: The summary variable scores for Building C.

Summary longitudinal results for Building C are shown in Figure 17. The building represents the shortest period between BUS surveys of 26 months. The surveys bridged the retrofit of dynamic external insulation (Figure 7). The BUS survey results were used to manage staff expectations of anticipated improvements to the building's thermal performance.

The context nesting identified two changes: the addition of auxiliary mechanical ventilation, and local boost controls for the auxiliary ventilation in the large open-plan offices. However, in practice the ventilation system usually operated automatically in boost mode without the occupiers' intervening. The lack of statistical movement in scores for control over ventilation is therefore consistent with the evidence.

The statistics show a strong consistent signature for the survey's 13 summary variables, with no statistical movement for 12 variables, and similarly no movement for the control variables (Figure 18). Of the six comfort variables already below scale midpoint in 2013, five had shown a (non-statistical) decline, including all thermal and air quality variables. However, it can be seen that the mean scores for summer conditions in 2013 were already extremely low before the retrofit. That the mean scores were lower after the retrofit (albeit not statistically) may indicate that scores could not decline much further even if conditions, post-retrofit, had not met expectations.

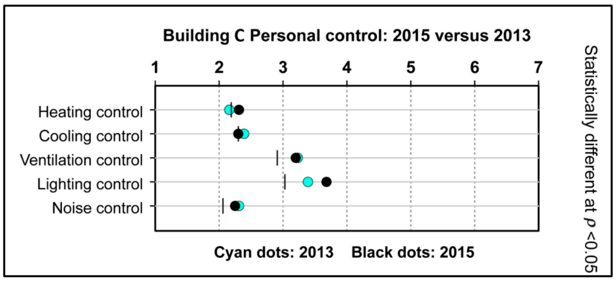


Figure 18: Building C scores for control over environment.

Evidence for the fall in comfort scores (albeit non-statistical) was sought in the long-term physical monitoring. Prior to the retrofit the building was found to suffer extreme overheating. Room temperatures in all occupied spaces prior to the external insulation rarely dropped below 21°C and often rose to 28°C and above during working hours, particularly in south-facing offices. Internal monitoring for June 2013 indicated that internal temperatures in the south-facing open-plan offices on both floors fluctuated between 24-27°C during occupied hours, and rarely dropped below 22°C.

After the refurbishment internal temperatures were found to be no better, irrespective of season. For the Christmas period 19-30 December 2014, ground floor internal temperatures did not drop below 22°C and sometimes peaked at 26°C. For other periods, the monitoring showed that the building consistently retained heat at nights and at weekends. These were conditions that the external insulation could not solve and may even have exacerbated.

Building C's enduring comfort signature is considered striking given that only 33% of the 53 respondents to the 2013 survey were identified as taking part in the 2015 survey (*n*=66). The sampling difference is a product of the building's highly peripatetic (although largely long-term) workforce.

The comfort signature concept is challenged by the statistical movement in scores for perceived productivity, which were statistically higher in 2015.

There is no physical evidence that may explain this difference. It is counter to all other comfort distributions, as well as the evidence from the monitoring and the context nesting. It is possible that the statistical difference may be related to the highly mobile workforce and therefore may account for some variance in the data. However, *ipso facto* this explanation must also apply equally to all other comfort variables, and it does not.

Therefore, while the productivity mean scores for both surveys remain below BUS scale midpoint and therefore consistent with other discomfort scores, the longitudinal statistical difference between the productivity distributions (at $\rho = 0.0374$) remains an exceptional and unexplained statistical outcome.

The summary results for Building D are shown in Figure 19. As the only school in the dataset (therefore dominated by classrooms with low adult occupancy) it was suspected that its comfort scores may be typology-sensitive and therefore exhibit different characteristics to the office pilot studies.

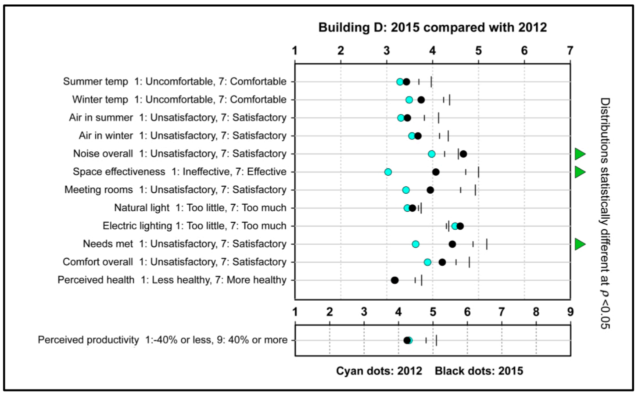


Figure 19: The summary variable scores for Building D.

As the school is a combination of 12 linked but separate structures, it was not possible to construct a unified context nest. Similarly, it was not possible to break down the survey sample for each structure as this would result in sub-samples too small for statistical analysis. Nevertheless, despite the provisos, it was found that triangulating between the contextual changes, the free-text feedback and the longitudinal movement in comfort scores delivered results surprisingly similar to the office studies.

Although the summary scores exhibited a strong comfort signature for the building, this was partly expected given the short (three-year) gap between surveys. Nonetheless by 2015 three distributions exhibited strong statistical improvements: 'noise overall' ($\rho = 0.0184$), 'space effectiveness' ($\rho = <0.0001$) and 'needs met' ($\rho = 0.0056$). Possible reasons were sought in the contextual evidence.

In 2013 the building was known to suffer thermal and air quality problems, with teaching staff highly critical of the inadequacy of the open-plan teaching spaces in terms of noise, lack of storage, and wasted inflexible space (Kimpian *et al*, 2015). Following the 2013 BUS survey the school invested in additional walls and partitioning to enclose previously open spaces and thereby improve acoustic and visual privacy. Additional storage was provided in some areas.

For testing for statistical movement between surveys, the teaching communities in the 2012 and 2015 samples were disaggregated (n = ~30 and ~34 respectively) to check for statistical movements. As a consequence, of the 24 variables, satisfaction with natural sources of glare had marginally worsened (ρ=0.0504) while perceived control of lighting was statistically worse ($\rho = 0.0158$). As with the whole building sample, satisfaction with space-use effectiveness among teaching staff was statistically higher. However, the small samples for teaching staff are considered on the margin for robust statistical testing.

Overall, the statistical longitudinal movements in perception scores at Building D are considered to be merely consistent with the known contextual changes rather than evidence of strong causal associations.

Results: Stage 2 studies

The outputs from the initial pilot studies prompted additional research questions:

- Does occupant satisfaction decline or improve with as offices change layouts from cellular to open-plan offices?
- Do longitudinal occupant comfort perceptions in some contexts exhibit a change (improvement or decline) in accordance with movement in other comfort and satisfaction variables?
- Where changes (a decline or improvement) are found in specific occupant satisfaction variables, does this decline equate to a reduction in perceptions of overall workplace health, comfort and productivity?

Improvements were made to the research design. As a consequence of findings at Buildings A and B, a question was added in the BUS survey on satisfaction with toilets. While the resulting data could not be analysed longitudinally, it was considered important to triangulate scores for satisfaction with toilets with contextual evidence mapped in the context nests, particularly regarding the spatial and social density calculations.

The summary results for Building E are shown in Figure 20. Building E was the only building in the research dataset where spatial density had fallen in the eight years between surveys. Figure 20 shows that Building E's comfort signature is disrupted by both statistical declines and improvements for six of the 12 summary variables. For the occupant perceptions to be upheld as reliable indicators of these longitudinal changes, explanatory evidence needed to be found in the context nests and free-text reports.

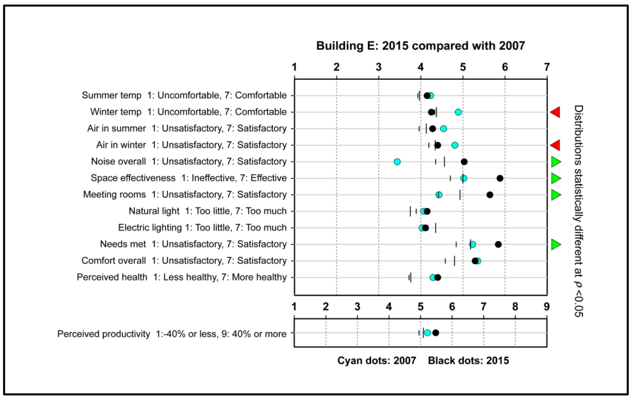


Figure 20: The summary variable scores for Building E.

The greatest statistical movement was in satisfaction with noise. In 2007 dissatisfaction with noise conditions was attributed to a single tenant of a large open-plan ground floor office. However, on investigation it was found that, statistically, discomfort with 'noise overall' occurred on both floors and across separate tenants.

Meta-analysis of the five noise sub-questions in the BUS survey identified longitudinal statistical differences in sample distributions for 'noise from people' ($\rho = 0.0071$) and 'unwanted interruptions' ($\rho < 0.0001$). All distributions for noise variables had improved between 2007 and 2015, including that for control (Figure 21). Staff in both years did not identify 'noise from colleagues' as a problem, suggesting that discomfort stemmed from general background noise.

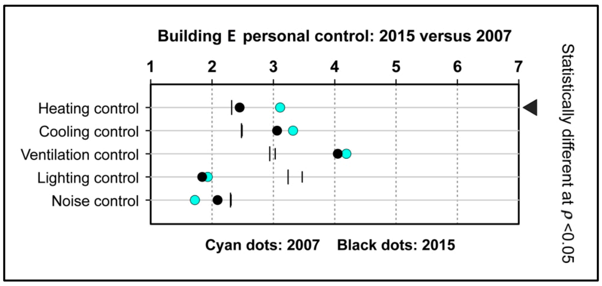


Figure 21: Building E scores for control over environment.

The context nest data were analysed for possible causes. In 2007 the tenanted building housed 300 people (design capacity 500), whereas in 2015 occupancy had dropped to 260, with only 157 reported to use the building on a regular basis. Utilisation rates for the 70% open-plan offices were not known in 2007, but in 2015 they were known to vary considerably between 20% and 70% depending on tenant. Therefore, overall, the building in 2015 was very lightly occupied compared with 2007. Only in one tenancy could density be higher than BCO norms (BCO, 2014), at one person/6.3 m^2, but known utilization rates meant that this space was running no denser than one person/13.2 m^2.

Other spaces were running better than one person/12.6 m^2. One 417 m^2 open-plan office was running consistently at one person/34.7 m^2. Such generous spatial densities support the statistical increase found in scores for 'space effectiveness', 'meeting rooms', and 'needs met'. While all three variables had scored well in 2007, they had improved statistically in 2015.

The statistical scores were supported by analysis of the negative and balanced comments in 2007, where noise complaints were double the comments made about other comfort variables. The contextual evidence therefore suggests that the naturally ventilated building, with its abundance of hard surfaces and exposed thermal mass, may be aiding noise transmission and high levels of speech intelligibility at when the building has social densities at or near to design expectation.

Despite the high functional scores, staff in 2015 scored winter conditions statistically lower, with the sample distributions for winter temperature ('too hot' to 'too cold') statistically 'too cold' at $\rho = 0.0008$. The change is mirrored in statistically lower scores for heating control (Figure 21).

Although the contextual evidence did not include operational data for the intervening eight-year period between surveys, in 2015 the landlord was investing in additional heat-raising capacity as the building had been found to be consistently too cold. Fan heaters had been provided to staff in one tenancy to overcome discomfort. It must be noted that all seasonal scores remained above scale midpoints, despite statistical movement in winter comfort scores. This indicates that while staff were statistically less comfortable they were not uncomfortable, possibly due to the landlord's interventions.

Building F represented the longest gap between BUS surveys of 21 years. The building was remodelled for multiple tenancies in 2008 by sub-dividing the massive floor plates and replacing the building's central meeting room complex and central toilets with a day-lit atrium as a common thoroughfare.

The context-nests captured many dimensional and physical changes to the office areas, but were limited in capturing the full range and extent of structural alterations.

The context nests recorded the changes relevant to the office areas: the conversion of mixed-mode ventilation to full air-conditioning, and the replacement of the metal-halide uplighters by conventional suspended fluorescent fittings. In other respects, the open-plan tenant spaces retained most morphological details of the original 1990s design, notably the 4.2 m-high exposed coffer concrete ceilings.

The summary results for Building F are shown in Figure 22. It was hypothesised that Building F's comfort signature might be weak or non-existent given the passage of time and the extent of the changes. Furthermore, some functionality questions in the BUS survey were not present in the 1995 version, limiting the longitudinal comparison.

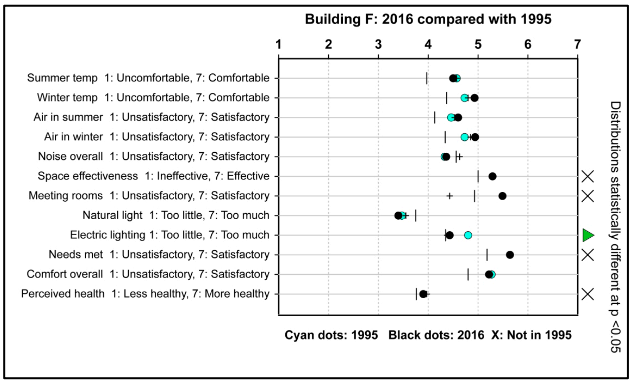


Figure 22: The summary variable scores for Building F.

Crosses in Figure 22 signify the four summary variables not covered in 1995.

The 1995 survey was based on a one-in-four sampling frame in the wholly open-plan building. This delivered 119 responses (a statistically valid sample), whereas the 2016 survey simply aimed for the highest possible response rates from the occupied tenancies. As two tenancies are in offices created in 2008 from the former third-floor staff restaurant, the 112 responses from that floor were omitted from the longitudinal analysis.

The degree of longitudinal uniformity shown in Figure 22 is considered remarkable given the passage of time and the changes in the building. Only one comfort variable was statistically better than in 1995, that of satisfaction with 'lighting overall'. This could be associated with the replacement of the original problematic electric lighting.

The uniformity extended to the entire 24-variable dataset. Although perceived productivity was statistically lower ($\rho = 0.0002$), it was still above scale midpoint.

The response distributions for control variables showed statistical loss of control between 1995 and 2016 for the sample distributions for personal control of ventilation and lighting (Figure 23). The context nest provided evidence for the movement: the metal halide uplighters were controlled locally in 1995 whereas in 2016 the fluorescent downlighting was automated on presence detection. The perceived loss over control of ventilation is consistent with the permanent closure of the perimeter sash windows.

The satisfaction score distributions for all 24 comfort variables were checked against the 1995

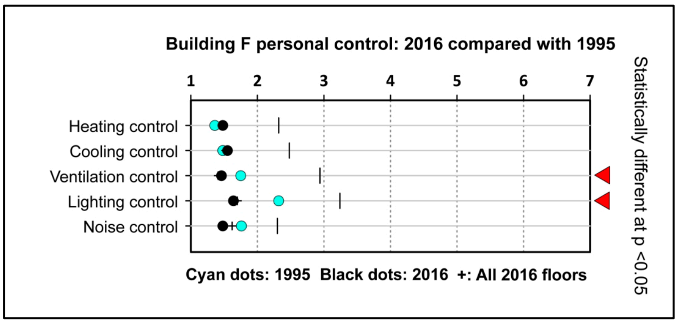


Figure 23: Building F scores for control over environment.

scores for four tenancies where sample sizes were statistically valid. Additionally, the current spatial, social and effective densities for each tenancy were calculated (the latter at a default utilization factor of 70%) over the occupied office areas to provide a check for relationships of occupant density with comfort perceptions.

Staff in tenancies occupying the original office areas generated scores statistically consistent with the whole building distributions. This may be expected, as the largest two tenancies accounting for around 53% of the total 2016 sample. However, control over noise was statistically lower in the two large tenancies. There was no obvious cause, other than population densities calculated to be one person/5.3 m^2 and one person/6 m^2 based on quoted occupancy data. The densities only meet BCO norms at 70% utilization. Conversely, control of noise was scored higher by the two tenants in the new third floor offices (statistically so for one tenant) compared with 1995. In these offices the densities were unusually generous, at one person/14.1 m^2 and one person/19.6 m^2.

In tenancy F2, the scoring distribution for 'control over ventilation' generated an anomalous statistical result. In the other tenancies of the original offices, control over ventilation had dropped statistically, consistent with the loss of openable windows on those two floors. This meant that if no explanation could be found in the context nest for the tenancy, the statistical anomaly would need to be reported as a major limitation of the research methodology and the use of the BUS survey as a reliable longitudinal tool.

However, subsequent investigation revealed that staff in that tenancy had discovered how to unlock the sash windows ostensibly sealed during the refurbishment. While this covert action was in contravention of the building's operational policy, the occupants had inadvertently reported their surreptitious behaviour through their individual survey scores.

The context nests for tenancies (F3 and F4) on the third floor, created in the former restaurant during the 2008 refurbishment, recorded that architecture lacked the double-skinned façade and solar shading of the original lower floors. The third floor was also retrofitted with suspended ceilings to hide new air-conditioning units. The resulting floor-to-ceiling height of 2.7 m was consequently much lower than the original floors that retained the exposed concrete coffers.

Checks of the survey scores for tenancies F3 and F4 (*n* = ~50 and *n* = ~62 depending on question) revealed that the survey scores did not conform to the comfort signature found in the sample distributions for the original office spaces. The south-facing office (tenancy F3) was statistically less satisfactory for summer temperature and winter temperature (ρ <0.0001 and ρ = 0.0253 respectively), and 'too cold' in winter (at ρ = 0.0030). Scores for glare from sun and sky were also statistically lower (ρ = 0.0017) for the south-facing tenancy. Investigation revealed that the glare-control film added to the windows was inadequate, motivating some staff to stick large sheets of paper to the windows.

The comfort score distributions for the north-facing office (F4) were reversed for the seasonal variables, with no statistical declines and with statistical improvements over 1995 for summer air conditions (ρ = 0.0088). Electric lighting (ρ = 0.0057), 'noise overall' (ρ <0.0001) and control over noise were also statistically better.

The results suggest that the double-skin façade and high exposed thermal mass in the original offices may play a key morphological role in maintaining their longitudinal comfort signatures.

Although it was not possible to analyse satisfaction with toilet provision longitudinally for Building T (as the BUS question was new), negative and critical comments on toilets were between two and three times greater than any other comfort variable commented upon for the majority of tenancies.

The summary results for Building G are shown in Figure 24. Building G is one of two buildings for which three BUS surveys were conducted. The 2006 survey was conducted on the building in its pre-refurbishment state, after which the building was stripped back to its shell and core. While the refurbished building studied in 2010 was morphologically the same, its environmental systems and internal finishes were very different to the building as surveyed in 2006.

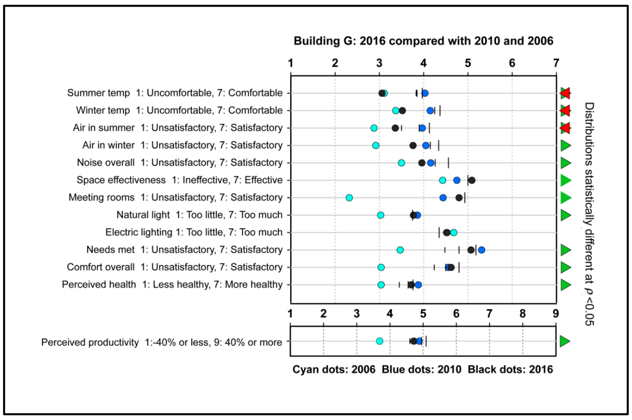


Figure 24: The summary variable scores for Building G.

The summary results for 2006 show a building perceived by its occupants to be performing poorly on all summary variables, with all scores below scale midpoint. Perceptions improved statistically in the 2010 survey for 16 out of 24 comfort variables studied in the research project. Perceptions for user control over cooling, ventilation and lighting were statistically lower as a consequence of the introduction of automated systems (Figure 25).

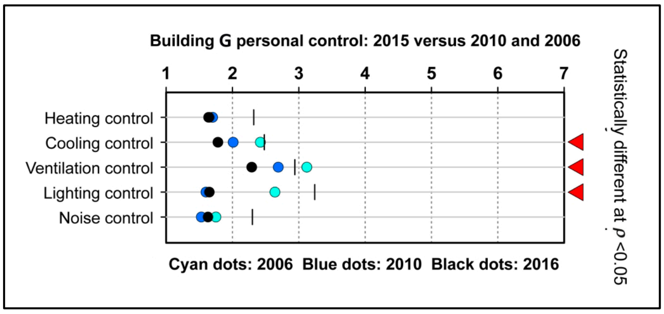
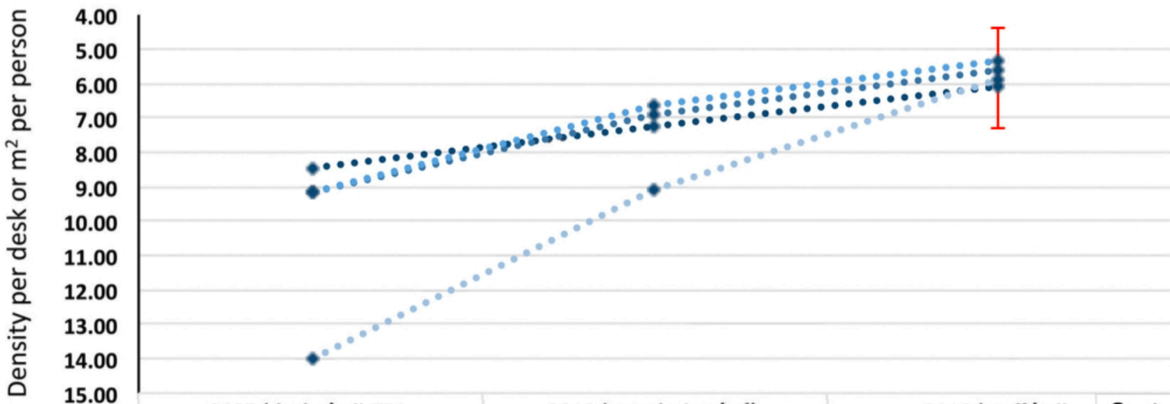


Figure 25: Building G scores for control over environment.

The lack of commonality in comfort perceptions in the 2006 and 2010 surveys (i.e. the lack of a distinct comfort signature) is thought entirely consistent with the context of a deep refurbishment. In contrast, the results for the 2016 summary variables show that a longitudinal comfort signature had developed similar to the 2010 survey distributions for electric lighting, overall comfort, needs met and



	2007 (desks/m²) TFA	2010 (population/m²)	2016 (staff/m²)	Quoted staff m²
Level 3	8.45	7.23	6.11	5.0
Level 2	9.17	6.93	5.60	4.6
Level 1	9.17	6.64	5.37	4.4
Level 0	14.02	9.11	5.89	4.8

Figure 26: Longitudinal changes in occupant density at Building G.

perceived health and perceived productivity. However, the seasonal comfort scores exhibited statistical decline (mostly at 99% levels of statistical difference) for satisfaction with summer and winter temperature, air conditions in summer, and glare from sun and sky. Perceptions for control of ventilation were also lower statistically compared with 2010.

Causes for the reversal of occupant satisfaction in the intervening six years between the post-refurbishment BUS surveys were sought in the context nest criteria and the free-text responses of the occupants. Some contextual drivers for the drop in satisfaction were immediately evident: local control of lighting with drop switches had been lost in the retrofit of automated lighting. Furthermore, user-controlled dimming of local fittings was rescinded by the facilities team after 2011, who then retrieved the occupants' hand-held lighting controllers. However, some staff retained their controllers illicitly, showing them to the researcher or making comments on their BUS forms.

Evidence behind the statistical drop in satisfaction with seasonal variables were not found in the context nest criteria, as the context nests did not capture the operational policies of the automated natural ventilation installed in the retrofit. For this, the research focused more heavily on occupants' free-text responses. Many respondents commented on the motorised windows being opened or closed at the wrong times, ineffective when open, and closed when conditions were hot. Some staff complained that manually opening the windows to alleviate discomfort led to facilities staff swiftly closing them again.

Calculations were performed on historic density patterns in building G. Floor plans, desk layouts, and occupancy data were obtained for the survey years. On-site laser measurements were compared with take-offs from scaled drawings to determine the occupied areas on each floor for each survey year.

The changes in occupancy densities quoted in Figure 26 are not wholly consistent between survey years as the units of measurement were subtly different based on the type and quality of data available. Nonetheless, cautious analysis indicates that densities had increased from industry norms of one person/8-10 m² (BCO, 2013) to between one person/4.4 m² and one person/6.11 m² at full utilisation. At a generic utilization of 70%, the densities throughout in 2016 were no better than one person /7.1 m².

Spatial and social densities were calculated for each level. The BUS response distributions for the 2010 and 2016 surveys were also disaggregated by floor and compared for statistical differences. Sample sizes were on the margin for statistical analysis (n = ~33 to 64 depending on floor). However, as response rates were high for both surveys (82%), the data are considered representative of the actual populations.

Statistically, longitudinal satisfaction in the building decreased with floor level. The top floor (Level 3) showed the greatest decrease in comfort perceptions compared with 2010, with large longitudinal skews in the sample distributions for most seasonal variables, with seven variables changing at or below $\rho = 0.0028$. For example, the mean score for satisfaction with summer temperature was 1.81 – a score that would be at the extreme end of any 1-7 BUS benchmark dataset. However, scores for the outcome variables of 'needs met', 'overall comfort' and 'perceived productivity' did not move statistically on any of the floors.

In the midst of such extreme perceptions of discomfort it is important to report that survey respondents were willing and able to differentiate between comfort variables. For example, respondents on all floors in 2016 reported statistical improvement in satisfaction with personal storage. This is a product of a known increase in filing cabinet capacity introduced after 2010 and captured in the floor plans (though not in the context nests).

Analysis of the negative and balanced comments also indicated that complaints increased with storey height, although not linearly. Levels 1 and 3 generated the most negative and balanced (i.e. critical) comments. Level 3 generated critical comments by half of the survey respondents for noise overall, overall comfort, perceived health and perceived productivity.

In general, excessive noise was the most oft-cited complaint, relating to noisy colleagues, poor acoustics and distracting speech. In the absence of data on the building's acoustic performance (the structure was exposed during the retrofit), the building's very high spatial and social densities are judged to be the cause.

Discussion

The longitudinal study of occupant satisfaction over periods of between three and 21 years offered an unprecedented opportunity to analyse the extent to which perceptions of satisfaction with a wide range of seasonal and functional comfort variables alter with changes in physical context. The results were considered against each of the research questions and discussed below.

Primarily, it was found that perceptions of occupant satisfaction in each building were found to be statistically stable over long periods, long enough for occupant turnover to reduce (if not eliminate) any incidence of matched-pair scoring working in the background. Statistical differences were able to be confidently associated with changes in physical, morphological and demographic contexts, as captured through records, field measurement and calculations, and observation.

Where descriptive statistics in the individual context nests were either inconclusive, partial, or insufficient to explain the statistical changes in occupant comfort or satisfaction perceptions, evidence was sought from the occupant free-text responses. In some cases the free-text feedback offered explanations for otherwise unaccountable statistical changes in perceived comfort scores (e.g. issues with toilet maintenance).

Only two statistical differences in comfort perceptions were unable to be associated with contextual changes: perceived productivity in one building and satisfaction with cleaning in another. The former may be due to the building's unusually highly-peripatetic workforce which led to large differences in the make-up of the population. In all other respects the strongly negative perceptions of the building's environmental characteristics were shared by most survey respondents. Not enough information on cleaning regimes was gathered to explain the statistical movement for satisfaction with cleaning in the one building where this was found.

In all other cases of statistical change in comfort perceptions, a likely contextual cause could be identified through triangulation of evidence. Statistical differences were therefore not found to be random. The patterns found in perception scores were therefore considered analogous to each building possessing a contextual comfort signature that persists over time unless and until a contextual factor motivates a change to perceptions. Reasonable and justifiable associations could be made between contextual changes and the occupant comfort perceptions. The statistics are not, however, Presented or suggested as being conclusive proof of causation. The evidence is instead presented as believable and trustworthy based on levels of rigour that is practically achievable when studying real buildings in use (Robson, 2011 p9).

The second stage studies found that changes in occupant comfort perceptions are related to changes in office layouts. Longitudinal movement was mostly in the form of decline in satisfaction, particularly as social densities increased. Statistical shifts were seen in changes from cellular and shared offices to open-plan, (notably in spaces not originally designed for open-plan working), and most clearly in spaces where measured densities (various combinations of workstation, social and effective density) had risen way in excess of established norms. Knock-one effects were seen in lower satisfaction with functional provision, such as toilets and storage.

Case-study buildings originally designed as open-plan offices were found to perform consistently well over long periods, at varying occupant densities and over a range of floor depths and ceiling heights. However, findings from the density analyses were consistent with many other studies of densely occupied open-plan offices, in that respondents were less satisfied with their lighting, acoustic, ventilation and temperature conditions as spatial density increased (Duval, Veitch, and Charles, 2002). Similarly, a review of office worker health and performance attributed negative occupant psychophysiological reactions (such as crowding stress) to office location, layout and usage (de Croon, Sluiter, Kuijer, and Frings-Dresen, 2005). The case studies also support the improvements found in perceptions of privacy, crowding and satisfaction where agile working policies had been introduced (Keeling, Clements-Croome, and Roesch, 2015).

The research sought to determine whether longitudinal movement in comfort variables were independent or co-dependent, i.e. whether scores given for some comfort variables were matched by statistical movement in scores for other variables, irrespective of contextual factors. The research found no evidence of influences in comfort scoring, rather that survey respondents discriminated in their scoring to the extent that each comfort variable was treated independently. This characteristic was reinforced by the fact that statistical changes in scores could be explained by contextual factors. Had a co-dependency of scores been detected, arguably they would have generated longitudinal statistical movements that would have no reasonable explanation. This was not the case.

No relationship was found in the longitudinal data linking statistical decline or improvement of environmental variables with statistical changes in perceptions of overall comfort, health and productivity. Commonsense suggests that there must be some linkage, but no patterns were found.

Generally, BUS occupancy survey studies treat statistics for overall comfort, health and perceived productivity as outcome variables: i.e. they are the products of contributing factors. Those three variables were categorized as such in this study. However, as no relationships were evident, the association between the so-called outcome variables and other environmental factors may be tenuous and possibly non-existent in reality. It is thought that perceptions of health and productivity in particular may be more influenced by factors outside the built environment, such as workplace and organisational factors and policies that are beyond the scope of a built environment survey such as BUS.

It is evident from the case studies that even where conditions were perceived to have declined over time, occupants' coping and adaptation mechanisms were at least partially able to counter any constraints created by the environmental conditions. It is therefore suspected that any relationship of environment conditions to perceived productivity – statistical or anecdotal – may only become evident when conditions decline to a point where occupants have run out of their capacity to tolerate, cope and adapt.

Notwithstanding the comments made above, the longitudinal studies suggest some relationship between the so-called outcome variables and workstation density. Occupants appear to favour lower densities. (There is also some evidence that occupants prefer spaces with higher ceilings, although no questions on ceiling heights are included in BUS.) That said, the research data are contrary: respondents appear to cope with workplace densities at, or greater than, the prevailing densities identified by the British Council for Offices (BCO, 2013), without those respondents reporting the consequences as being intolerable.

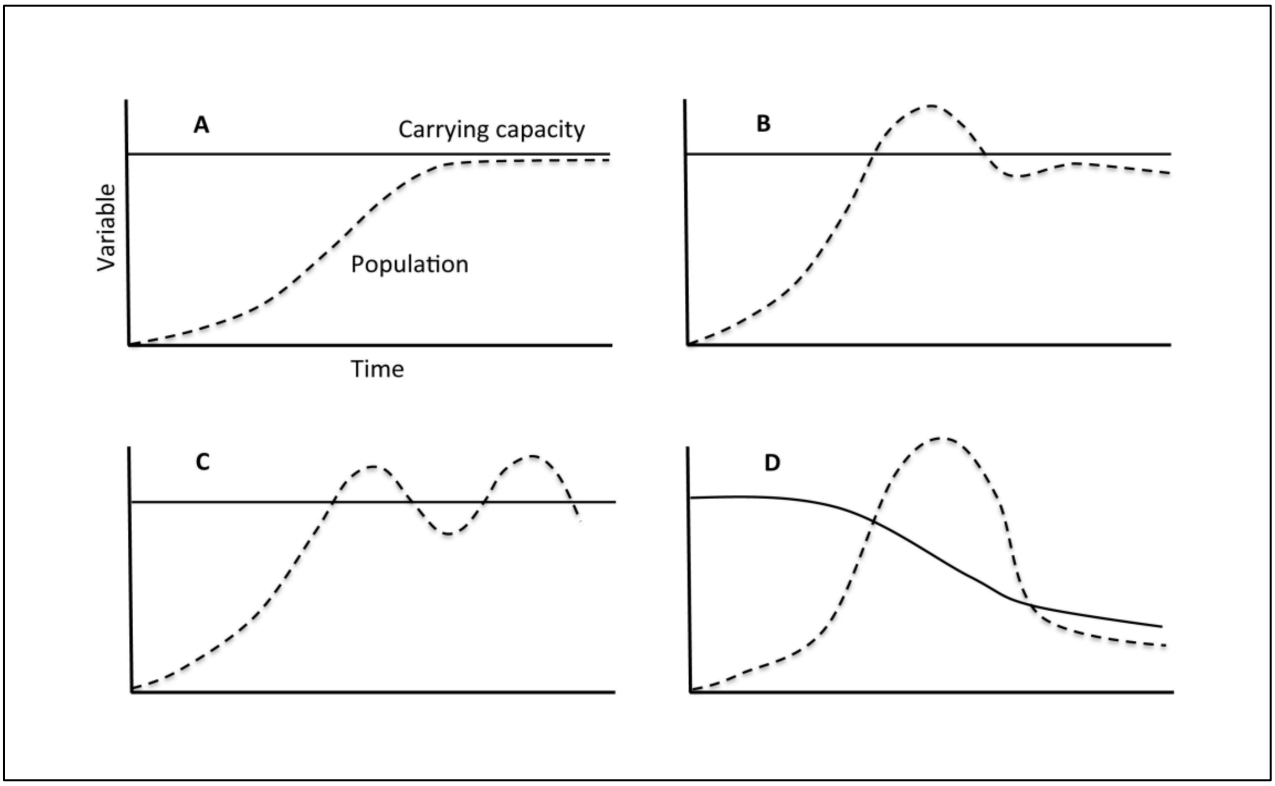


Figure 27: The four models of carrying capacity after Meadows *et al*, 1972)

Although the findings from a sample of seven buildings are not claimed to be generally representative of how buildings perform over time, commonalities nonetheless emerged that provide insight into the long-term relationships between buildings and the perceived comfort and satisfaction of occupants working within them. It is suggested that the findings are evidence of the degree to which occupant perceptions of environmental and functional conditions are influenced by changes in those factors - something that can only be assessed through longitudinal study.

In some cases the research found evidence of possible boundaries to acceptable levels of occupant comfort evidenced by statistical changes in comfort and satisfaction scores in the BUS survey, and that these may be linked to measures of occupant density. The boundaries are thought to represent the limits to a form of building carrying capacity (Bendewald, 2013).

Carrying capacity of offices

It is posited that the boundaries to occupant comfort – what they are, the forces that act upon them, and how they express themselves – could be expressed using models of 'carrying capacity' (Meadows, Meadows, Randers, and Behrens, 1972).

Meadows' four generic models were therefore considered for their applicability in using longitudinal occupant perception data as the primary dynamic mechanism for managing occupant satisfaction (Figure 27).

Model A is an example of a population growing over time to equilibrium, as defined by the boundaries and limitations of an environment. The latter represents a theoretical limit of carrying capacity, and the threshold a known quantity of a variable.

Model B offers a refinement: an example of a situation where a population has exceeded a threshold of carrying capacity at some point in time only to fall back to equilibrium. This could be prompted by knowledge of a carrying capacity threshold having been exceeded, thereby prompting a remedial reaction.

Model C is a refinement of Model B, where a population oscillates around a carrying capacity threshold. Model C reflects a dynamic state of a population. In buildings, this may equate to times when its features and functions are adequate for the population, and times when they come under stress, leading to a risk of discomfort and/or loss of utility. Model D characterizes a permanent loss of carrying capacity. Such drops might occur when a utility's function is permanently compromised by a population increase. A clear example from the case studies is toilet provision.

Of the four models, Model C is thought to most often represent the contexts found in the longitudinal office case-studies: e.g. a rise in population but with oscillation (or variability) around a threshold. It is hypothesized that where breaches in carrying capacity shown in Model C (and, to a certain extent, Model D) are known, periods of population overload may be predictable and therefore manageable, perhaps by deploying mitigation strategies developed for such events.

For this association to be supported, three pieces of evidence are needed: evidence of population rising over time, a defined value for a given comfort threshold (such as an original design allowance), and third, evidence of a (statistical) decline in occupant comfort perceptions.

For example, in Building B, there should be point at which staff forbearance with a range of discomfort factors could be exhausted, especially if density was allowed to climb uncontrolled at the observed rate. However, with just two survey points the tipping points at which staff lose their willingness to cope, adapt or tolerate conditions is unknown. As demonstrated by Buildings A and G, there is virtue in three or more survey points so that such functions can be plotted over time, and thereby evidence obtained of occupant reactions when a threshold is reached or exceeded.

Although the case-study evidence supports the basic characteristics of Model C, the relationship will undoubtedly be complicated by the characteristics of carrying capacity thresholds as they apply to occupied, bounded spaces like offices, and the natural reactions of people to the characteristics of those spaces. The human ability to tolerate, adapt, and cope with sub-optimal conditions or periods of discomfort may require carrying capacity thresholds to be applied with varying degrees of latitude. In this respect, some thresholds may act as bands than as fixed values. However, such bands could still possess an upper limit. Arguably, the closer that limit is approached, the more that people would resort to adaptation and coping mechanisms in order to remain comfortable and productive. Furthermore, the degree to which people are able to adapt and cope is thought to be partly dependent upon the level of control they are able to exercise (Leaman & Bordass, 2017). People with more control and greater freedom may be able to cope with wider ranges of conditions than those with no control and limited freedoms, further complicating the setting of carrying capacity thresholds.

Nonetheless, the weight of evidence from the longitudinal studies suggests that the concept of carrying capacity might provide a mechanism by which thresholds to occupant dis-satisfaction might be determined. This could aid building design and inform building management.

It is clear that for carrying capacity to be workable in a management process, effort will be needed to understand a building's morphological and physical context more fully. If it can be achieved, measures of carrying capacity may offer an alternative approach to managing occupant satisfaction in buildings than, for example, reliance on instrumented measurements. Although such measurements provide evidence of physical conditions to a high resolution, they are arguably weak at determining human behaviours. Carrying Capacity metrics may be way of detecting discomfort trends that might otherwise go unnoticed until they become so extreme that they become damaging to a business and expensive to solve.

Limitations

The research methodology possessed a range of limitations. Some were unavoidable, such as a lack of freedom of choice for when surveys could be carried out. This may have introduced some seasonal bias in the longitudinal comparison of occupant perceptions.

Future research may need to capture more dependent variables. Although this would likely increase complexity, labour time, and data management and processing, the following are thought desirable. For the context nest approach:

- Glazing ratio should be captured as an independent variable to make more sense of daylight and glare perceptions
- Floor depth-to-height ratios could be included as a potential independent variable for comparison

with a range of comfort responses (possibly supported by a survey question on ceiling height)

- Noise reverberation tests and speech intelligibility tests could be used as independent variables for multivariate statistical comparison with noise perceptions and density measurements.

The BUS survey itself was found to have some limitations. More free-text boxes are considered vital to enable respondents to explain their seasonal comfort scores.

Improved resolution would also be helpful in some categorical questions, such as age categorisation and proximity to windows. By contrast the additional question on toilet provision proved illuminating. Other limitations became apparent during the research. For example, it was found that longitudinal statistical differences in seasonal variables might be amplified by gender differences, accentuated by changes in gender balance over time. Figure 28 showed how females in each building survey consistently scored winter temperature a whole integer lower on the BUS survey scales when their fellow males were thermally neutral.

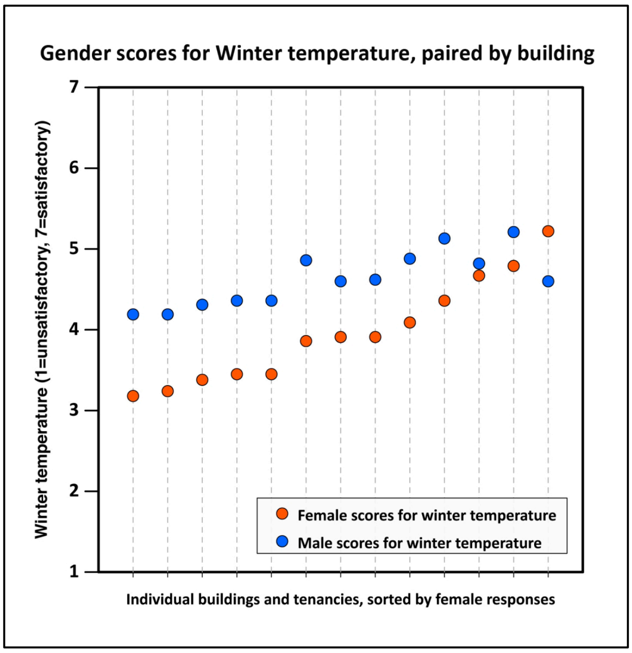


Figure 28: In most longitudinal surveys, females consistently scored winter temperature a whole integer lower on the BUS survey scales when males were thermally neutral.

Attempts to graph the trends and relationships between measures of spatial and social density and factors such as noise were thwarted by a shortage of data for buildings, tenancies and separate floors with low occupant densities. Figure 29 shows how perceived density and measured spatial density appear to have some relationship, but the correlation is statistically weak. Similarly, overlaying perceptions of noise on both measures of density shows a possible trend, but the relationship is similarly weak.

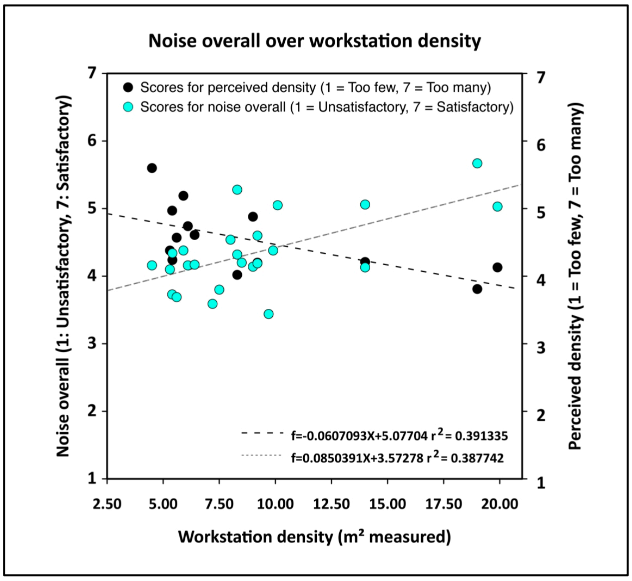


Figure 29: Comparison of the distributions for perceived density and noise overall over measured density for all office longitudinal surveys and tenancies where sample size permitted (i.e. $n \geq 50$). Statistical significance is severely limited by shortage of data for densities above 1 person/15 m^2.

Much more data is therefore required before relationships between physical (context nest) data and occupant satisfaction can be determined with any degree of certainty. This justifies more longitudinal case studies using the methodology described in this paper.

Although all occupant surveys were superficially identical, there were differences in data quality, particularly in data entry but also shortcomings in the level of detail behind survey data, such as incomplete records for floor or departmental location. This reduced the potential for sample disaggregation and therefore longitudinal comparison of some subsets.

Although the variables of perceived health, comfort and productivity were classified as 'outcome' variables, the lack of any relationship in perception scores with declines in other comfort variables – some extreme – suggests that the relationships between human perceptions of health and productivity and other comfort variables may neither be strong nor repeatable. In that respect, it is suggested that each building should be treated as an individual case, with attempts to generalize research findings across buildings (and building typologies) for factors such as perceived productivity exercised with great caution.

Conclusions

The longitudinal research presented in this research is considered a first step on a longer journey: a springboard to further research into the component parts of the carrying capacity of buildings. Greater certainty about the longitudinal relationships between comfort perceptions and contextual drivers may justify relaxation of statistical thresholds for quoting changes in comfort perceptions, and thereby lead to more nuanced conclusions.

The occupant survey-based longitudinal research reported in this paper suggests that buildings may possess individual comfort signatures, and that these signatures prevail until contextual changes alter the perceptions of the occupants. It is advanced that these perceptions can be robust enough to inform a mechanism for identifying context-specific thresholds of discomfort, and potentially a route for managing those thresholds using the concept of carrying capacity.

The carrying capacity theory is thought to have potential value for construction projects where there is a period of extended aftercare provided by the design and construction team. The three-year Soft Landings extended aftercare process, for example, contains allowance for at least two occupant surveys (Bordass, Bunn, Leaman, and Way, 2014). The results from those longitudinal surveys could be used to populate the carrying capacity characteristics for management of comfort and satisfaction beyond the nominated Soft Landings period. This would provide the end-users with a Soft Landings legacy that would extend beyond the extended aftercare. It could also provide a route for members of a project team to maintain an ongoing relationship with the building owners, helping to assess and advise on interventions and decisions affecting longitudinal performance against the satisfaction thresholds.

These arguments apply equally to any aftercare and post-occupancy assessments carried out by architects and engineers as part of their professional appointments.

It is recommended that future longitudinal study of occupant comfort and satisfaction needs to build upon the methodology explained in this paper. More needs to be known about interactions between comfort variables before any carrying capacity thresholds can be reliably determined. Research designs may also need to expand to include aspects of workplace design and measures of wellbeing, both of which were outside the scope of this research project.

Many statistical declines in comfort and satisfaction scores appear to be related to one or more of the three measures of occupant density. Hence it is also recommended that future longitudinal studies attempt to correlate changes in occupant satisfaction with both perceived and measured actual densities, with researchers taking particular care to accurately define a building's occupied zones. Net area measurements that include non-occupied spaces may lead to category errors and reduce the validity of statistical analysis.

Future occupant surveys are also recommended to include a question on perceived density as standard. It is also recommended that researchers strive to obtain a firmer grasp of actual social density and occupant utilisation rates, especially for offices.

The lack of a longitudinal relationship found between occupants' reported health, productivity and comfort and their satisfaction with other satisfaction variables (as measured by the BUS survey) requires a word of warning. Much recent research into comfort and productivity, cited earlier, has been based on large cohort databases, with very little contextual detail beyond building age and typology. Multivariate statistical analysis conducted on such databases with little or no morphological, operational and longitudinal context may force researchers to place undue reliance on statistical analysis, and thereby try and infer more from significant ρ values than those values are truly able to explain.

Overall, it is proposed that research outlined in this paper has demonstrated that analysis of occupant comfort responses cannot be performed in a contextual vacuum, where key characteristics of occupied spaces – whether dynamic (like occupant densities), or fixed (like building morphology) – are not included in a research design. It has also been demonstrated that such characteristics are pre-requisite to a proper understanding of the component parts of occupant satisfaction in buildings. *Ergo*, it is recommended that some form of rigorous and systematic context-mapping of characteristics should always be employed by researchers if they are to make sense of occupant comfort perceptions, and in order to understand the longitudinal movements in those perceptions that occur over time.

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