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Continuous IEQ Monitoring System: performance specifications and thermal comfort classification

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Abstract

The quality of buildings can be assessed in terms of the indoor air quality, thermal comfort, lighting quality, acoustic comfort afforded the occupants, collectively referred to as Indoor Environmental Quality (IEQ). A major barrier to a more thoroughly representative audit of actual IEQ performance are the expense and complexity of the measurement instrumentation required. Rapid developments in sensor technology in recent years present the opportunity for continuous and pervasive IEQ monitoring to deliver truly representative characterisations of building performance at a modest cost. The last remaining obstacle to realising these developments seems to be a concern about instrument accuracy.

In this paper we test the performance of a low-cost IEQ monitoring system (SAMBA) introduced in an earlier paper. Calibration data from 100 devices was analysed to calculate the standard error of the estimate as a measure of equipment accuracy. Those performance specifications were used in a Monte Carlo simulation based on measurements of thermal comfort parameters from 24 office buildings. Performance measures suggests the low-cost system, whilst not as accurate as laboratory equipment, is more than sufficient for building IEQ diagnostics and compliance assessments. Furthermore, the results of the Monte Carlo simulation show that continuous monitoring systems are better at characterising long-term performance than ad hoc measurement strategies using precision equipment. Low-cost pervasive monitoring

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technologies therefore offer a unique opportunity to improve our quantitative understanding of, and response to, indoor environmental quality issues.

Keywords

Indoor environmental quality; continuous monitoring; building performance; sensors; standards; thermal comfort

Highlights

- Reviews standards for instrument specifications and IEQ measurement protocols
- Evaluates the performance of 100 low-cost continuous IEQ monitoring systems
- Monte Carlo methods test the performance of different sensors for continuous monitoring
- Show continuous monitoring is better than spot measurements for long-term comfort assessments

1. Introduction

There are currently two fundamentally different strategies for the instrumental evaluation of Indoor Environmental Quality (IEQ) in buildings (ASHRAE 2010). The first is a low-cost approach based on a quick “snapshot” of environmental conditions with the aim of diagnosing gross underperformance or malfunctioning building services. The alternative approach, in-depth IEQ evaluation, is a more accurate diagnostic procedure, but is still inadequate for purpose of fairly representing the overall IEQ performance of a particular building because it too is conducted at a single point in time and at just one or two specific locations on the building’s floor plate. In view of the inherent spatial and temporal heterogeneity of IEQ parameters within a building, it is surprising that one-day spot measurement strategies persist as the dominant practice.

Comprehensively characterising the *variability* of IEQ parameters within an occupied zone of an office building with instrumental measurements cannot be accomplished using traditional spot-measurement methods due to exorbitant equipment and human resources costs. In response to this, recent standards such as EN-15251 (CEN, 2007) permit long-term temperature measurements from Building Management Systems (BMS) to be used when determining thermal comfort compliance. Whilst this acknowledges the importance of continuous monitoring, it does not convincingly address concerns over fair representation of actual thermal conditions as experienced by the occupants (i.e. wall-mounted sensors). But in the years since EN-15251 was published a new class of sensor technology has emerged from the ‘smart buildings’ sector (Navitas Capital 2018) that perform continuous IEQ monitoring by pervasive, low-cost autonomous systems embedded throughout the building’s occupied zones. The previous paper in this series discussed how a quickly-evolving technological context and increased awareness of IEQ concerns has led to the recent development of these IEQ data acquisition systems, such as SAMBA (Sentient Ambient Monitoring of Buildings in Australia), to meet the monitoring requirements of the commercial building sector.

Mobile carts laden with laboratory-grade equipment (see Heinzerling et al. 2013 for a review) have been used extensively in IEQ field research programs (e.g. Nicol and McCartney, 2000; Cena and de Dear, 1999; Benton et al., 1990; Chiang et al., 2001;

Kim and Haberl, 2012) and often accompanied occupant surveys as a way to ground-truth the subjective responses. In contrast to the cart solution, continuous monitoring systems combine low-cost sensors and relatively powerful micro-controllers into an autonomous 'turn-key' IEQ monitoring solution. Mainstream uptake of enabling technologies, particularly within the open-source community, has allowed researchers in disparate fields to develop such systems without significant capital investment. Most were designed primarily for use in office environments (e.g. Ali et al., 2016; Edirisinghe et al., 2012; Mui et al., 2016; Salamone et al., 2015; Scarpa, 2017) or residential settings (e.g. Carre et al., 2018). These studies are excellent examples of prototype systems, but they are limited by either undocumented testing protocols or performance assessments on single or small batches of devices. As a result, the performance of a continuous IEQ monitoring system in a large-scale deployment remains unreported in the research literature.

Since the most important advantage that these systems hold over traditional measurement cart approaches is their pervasiveness, a thorough assessment of performance across a fleet of such devices seems timely. Concerns over the accuracy of low-cost continuous measurement devices often exclude the entire product class from any serious application of building performance assessments. It is widely-accepted that low-cost systems are generally less accurate than laboratory counterparts, but this ignores the ability of pervasively deployed continuous monitors to provide insight into IEQ variability in both the spatial and temporal realms. Multiple devices placed across a floor plate sampling key IEQ parameters with sufficient accuracy provides a more representative picture of the *total* indoor conditions experienced by a building's occupants than a single-point measurement with laboratory-grade equipment mounted on a mobile cart. Recognizing this benefit, along with non-specialist installation and operation, has prompted increased interest in continuous monitoring for building performance assessments, notwithstanding sensor inaccuracies.

Given the measurement objectives for continuous IEQ monitoring in the buildings sector, concerns regarding sensor accuracy are somewhat obfuscatory. The more useful question to ask is what the known sensor inaccuracies imply for the representativeness of IEQ performance assessments, particularly in comparison to single-point sampling methods. Therefore, the principal aim of this paper is to address this question. The intention is to highlight the trade-off between equipment accuracy and representativeness in sampling spatio-temporal surfaces of IEQ conditions. The specific aims include:

- Review the relevant industry standards and guidelines regarding instrument specifications and measurement protocols in the context of building IEQ performance assessment,
- evaluate the performance of a low cost, continuous IEQ monitoring system (SAMBA) in what is, as far as the authors are aware, the first large-scale analysis of a device of this type,
- perform a Monte Carlo simulation to determine the adequacy of different measurement technologies to fairly characterise IEQ variability in office environments.

2. Indoor Environmental Quality Standards

Numerous regulatory documents relating to the assessment of IEQ performance of buildings have been published to date. They serve as reference documents representing consensus thinking within the building sector and have been developed by technical experts and stakeholders working together through technical committees and working groups (see Olesen & Parsons 2002 for a description of the Standards process). Standards that contain metrological considerations for measurement of physical quantities often include equipment performance specifications such as accuracy and error. The following section collates equipment specifications and recommended sampling procedures from standards (see table 1) relevant to measurement in commercial offices across the four categories of IEQ.

Table 1. List of relevant standards for IEQ measurement and classification.

Relevant Standard by IEQ Category	Organisation
Thermal Comfort	
Standard 55-2017 - Thermal Environmental Conditions for Human Occupancy	ASHRAE; ANSI
7730:2005 – Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria	ISO; CEN; BSI
7726:2001 – Ergonomics of the thermal environment – Instruments for measuring physical quantities	ISO; CEN; BSI
Indoor Air Quality	
*WHO guidelines for indoor air quality: selected pollutants (2010)	WHO
*WHO air quality guidelines: global update (2005)	WHO
Standard 62/1-2016 – Ventilation for Acceptable Indoor Air Quality	ASHRAE; ANSI
Lighting	
RP-1-12 American National Standard Practice for Office Lighting	ANSI; IES
12464-1:2011 – Light and lighting - Lighting of work places - Indoor work places	CEN; BSI
13032-1:2004 – Light and lighting. Measurement and presentation of photometric data of lamps and luminaires - Measurement and file format	CEN; BSI
Acoustics	
S12.2:2008 – Criteria for Evaluating Room Noise	ANSI; ASA
S1.43:1997 – Specifications for integrating-averaging sound level meters	ANSI
61672-1:2013 – Electroacoustics – Sound Level Meters - Specifications	IEC

* guideline document that is often cited in lieu of a comprehensive standard

2.1 Thermal comfort

The two most prominent standards pertaining to the assessment of thermal comfort in moderate indoor environments are ASHRAE Standard 55 (ASHRAE, 2017) and ISO 7730 (ISO, 2005). The geographic scope of ISO 7730's applicability is confined to countries that are ISO members, but this standard is predominantly used throughout Europe, whilst North American and Asian counterparts rely more heavily on ASHRAE Standard 55. Historically these two standards have evolved in parallel (Olesen & Parsons, 2002; Roaf et al., 2010) and both refer to adult human thermal comfort based on heat-balance methods developed by Fanger (1970) such as the predicted mean vote

(PMV) and its associated Predicted Percentage Dissatisfied (PPD) index. Other considerations such as local thermal discomfort, adaptive comfort, and non-steady-state comfort are also addressed.

ISO 7730 lists three categories of thermal comfort performance, with the highest level (Class A) specified as -0.2 < PMV < +0.2, with the units referring to a seven-point thermal sensation scale in which the central point is described as "*neutral*". To achieve that level of confidence in a PMV calculation requires high-precision equipment that complies with the 'Desirable' specifications as detailed in a companion standard, ISO 7726 (ISO, 2001), which contains the performance criteria for measurement devices for common environmental quantities relevant to thermal comfort along with details of different indoor environmental sensor technologies and metrological considerations. In addition to the measured environmental variables, ISO 7730 requires two so-called "personal variables" to be estimated for the population of building occupants to which the PMV, calculations are being applied. These are discussed in detail in companion standards ISO 8996 (ISO, 2004) for metabolic rate and ISO 9920 (ISO, 2007) for clothing insulation. Whilst the precise measurement of the two personal variables is beyond the scope of this paper, they are known to present a greater source of uncertainty in PMV calculations than the four environmental variables (e.g. Havenith et al., 2002; Gauthier, 2013). For this reason, the Class A thermal comfort specification type in ISO 7730 has been criticised by Arens et al. (2010) and Nicol & Wilson (2011) as being too difficult to determine, particularly considering that estimation errors are additive, and such narrow ranges having negligible implications on actual occupant comfort. ASHRAE Standard 55-2017 does not specify performance criteria other than 90% and 80% thermal acceptability classes (based on PPD estimates), but it does set out minimum environmental instrumentation performance specifications that are comparable to the 'Required' level in ISO 7730 / ISO 7726 (see table 2). These measurement-related sections of ASHRAE Standard 55-2017 are informative and therefore less scrutinized than other normative sections.

Table 2. Summary of instrumentation requirements for thermal comfort assessments in the prominent standards.

	ISO 7726:2001	**ASHRAE 55-2017**
Air Temperature		
Range:	10 to 40°C	10 to 40°C
Accuracy:	Required: ± 0.5°C Desirable: ± 0.2°C	± 0.2°C
Mean Radiant Temperature		
Range:	10 to 40°C	10 to 40°C
Accuracy:	Required: ± 2°C Desirable: ± 0.2°C	± 1°C
Humidity		
Range:	0.5 kPa to 3.0 kPa	25 to 95%
Accuracy:	± 0.15 kPa	± 5%
Air Velocity		
Range:	0.05 m/s to 1.00 m/s	0.05 m/s to 2.00 m/s
Accuracy:	Required: ±(0.05 + 0.05va) m/s Desirable: ±(0.02 + 0.07va) m/s	±0.05 m/s

While detailed instrument specifications in the thermal comfort standards serve to ensure reliability of indoor environmental measurements, there is another major source of error, namely the spatio-temporal sampling procedure and the measurement protocol. ASHRAE Standard 55 is more prescriptive than ISO 7730 in this regard and includes general advice on measurement protocols such as instrument positioning (e.g. centre of the room, 'representative', where the most extreme values are expected to occur) and temporal sampling (e.g. 'representative' measurements made over at least 2 occupied hours, air speed averaged over three minutes or less, other parameters five minutes or less). Olesen & Parsons (2002) suggest that guidance on the measurement strategy for the PMV/PPD input parameters within ISO 7730 is perhaps not exacting enough, and additional questions concerning what is 'representative' of spatial and temporal inhomogeneity have been raised by Nicol & Wilson (2010).

Fair representation of indoor thermal environmental variability is likely to require measurements made over seasons to capture effects of changes in solar angles and synoptic weather patterns. ISO 7730 was updated in 2005 to include five methods for long-term evaluation of thermal comfort, three of which are included EN 15251 (2007). These evaluation methods preference design phase building simulation procedures, and generally employ the concept of 'degree-hour' criteria for PMV. Carlucci & Pagliano (2012) raised several concerns, including the spatial summation of temperature distributions (particularly in multi-zone buildings), the boundary discontinuity of compliance categories, and the omission of severity of exceedances in the EN 15251 evaluation procedures. ASHRAE 55 is more relaxed in the requirements of long-term assessments by permitting air temperature and relative humidity measurements from Building Automation Systems (BAS) to be used as inputs to its long-term performance protocols. Interestingly, there is greater tolerance around measurement accuracy for air temperature (± 0.5°C) compared to spot measurement requirements, and a longer maximum sampling interval of 15 minutes over 30 days or longer. Similar to ISO 7730, long-term assessments of thermal comfort are based on 'exceedance hours' outside the $-0.5 < PMV < +0.5$ interval during occupied hours for the specific assessment period.

2.2 Indoor Air Quality

Standards governing indoor air quality requirements for offices are less definitive than those regulating thermal comfort. Rather than comprehensive international standards, guidelines are derived from consensus within the research literature to minimise exposure to potentially harmful pollutants (see Abdul-Wahab et al. 2015 for a review). Criteria are usually expressed as threshold concentrations of contaminants above which negative health effects may occur. In non-industrial typologies, such as commercial office buildings, thresholds are set well below levels corresponding to serious health risk – signs of contamination are generally irritations or odour annoyance – and exposure duration is normally paired with thresholds in consideration of the health significance of a given pollutant. The following section will briefly review the relevant IAQ standards and guidelines on the compounds measured by a low-cost, continuous sampling system (SAMBA).

The most prominent international regulatory documents on air quality are those published by the World Health Organisation (WHO). *Air quality guidelines for Europe* (WHO, 2000), first published in 1987 and again in 1993, is the result of exhaustive review work by a panel of over 100 technical experts. Two supplementary documents address specific indoor pollutants: *WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide: Global update 2005* (WHO, 2005) was issued following new evidence on the health effects of those five pollutants, and

Guidelines for indoor air quality: selected pollutants (WHO, 2010) contains a comprehensive summary of the latest understanding on indoor air pollutants.

Closer to the domain of built environmental research, ASHRAE Standard 62.1 (ASHRAE, 2016) serves as a key reference document, particularly for carbon dioxide concentration as it relates to mechanical ventilation, and is often used as a proxy for general indoor air quality. For CO_2, ASHRAE sets a threshold of 700 parts per million (ppm) above outdoor air levels based on a steady-state mass balance relationship that ensures sufficient dilution of odours and bioeffluents. Although CO_2 is recognised as a reasonable indicator of outdoor ventilation rates, it might not be so relevant to diagnosis of overall indoor air quality (Persily, 1996).

Whilst the WHO documents collate detailed information on common contaminants, they remain largely silent on instrument specifications and sampling procedures. Filling the lacuna of IAQ measurement protocols is the U.S. Environmental Protection Authority's document titled *A Standardized EPA Protocol for Characterizing Indoor Air Quality in Large Office Buildings* (EPA, 2003). Along with the outline of 'core' parameters to be measured – temperature, relative humidity, CO_2, CO, particulate matter, VOCs, and formaldehyde – it also discusses common monitoring methods (both real-time in situ measurement and sampling for off-site analysis), as well as sampling procedures that draw heavily from cognate standards. Similarly, Appendix A of ASHRAE's *Indoor Air Quality Guide* (ASHRAE, 2009) offers general advice on IAQ monitoring strategies.

Reviews of the indoor air quality literature by Wolkoff (2013) and Sundell (2004) suggest that a rigorous scientific understanding of the exposure-response relationships for common pollutants in otherwise innocuous environments such as offices is still wanting. It is therefore difficult to determine necessary instrument performance specifications, which goes some way towards explaining the paucity of prescriptive standards or guidelines on IAQ instrumentation and measurement protocols.

2.3 Lighting

The Illuminating Engineering Society (IES) publishes the ANSI/IES RP-1-12 *National Standard Practice for Office Lighting* which covers the lighting requirements for regular office spaces. Approved by the American National Standards Institute (ANSI), it sets out, amongst other things, the distribution and minimum illuminance levels required for visibility in tasks such as reading and writing in different areas of an office. The European counterpart document, EN 12464-1 *Light and lighting - Lighting of work places – Part 1: Indoor work places*, is similar in scope and relates to visual comfort, visual performance, and safety of indoor occupants. Illuminance (in lux) is the most common measure of lighting quality as it's more readily accessible compared to other parameters like luminance and chromaticity. Discussion will be limited to illuminance as it is the indoor luminous environmental parameter most relevant to SAMBA's suite of sensors.

Illuminance is generally measured at the task area along either a horizontal or vertical plane, depending on the task requirements. For example, common office tasks like reading and writing require a minimum illuminance level as measured horizontally on the desk, nominally at a height of 0.75m above the floor. In addition to measurements of horizontal and vertical illuminance levels, uniformity of light in the task area is commonly derived. Both Mills & Borg (1999) and Osterhaus (1993) showed an increasing trend in recommended illuminance levels across international standards during the 20th century for all activity types. Recent flattening or reduction in targets are likely attributable to screen-based tasks replacing traditional paper-based reading and writing on horizontal surfaces for most office work, better lighting technologies, and greater uptake of task lighting. Emerging from these critical reviews are inconsistent recommendations on illuminance levels between countries and negligible traceable empirical evidence supporting those targets.

Whilst neither standard lists equipment performance specifications, reference is made to ISO/CIE 19476 *Characterisation of the performance of illuminance meters and luminance meters* or EN 13032-1 *Light and Lighting – Measurement and presentation of photometric data of lamps and luminaires*. Many specifications for photometric devices are given, including a maximum calibration uncertainty of 1% in the British Standard, but that appears to be targeted more at laboratory testing of lamps and luminaires which presumably would require greater accuracy and precision than field measurements of office illuminance levels would warrant.

Measurement protocols in both ANSI/IES RP-1-12 and EN 12464-1 focus on minimum illuminance and uniformity of light, with the latter parameter requiring a clear spatial sampling protocol. EN 13032-1 details the grid system approach to verifying compliance of illuminance levels for the task areas, as well as surrounding and background areas. However, there is little mention of the temporal frame of measurements in either standard. Both standards state that minimum illuminance levels can be provided by daylight, artificial lighting, or a combination of both. Measurement protocols in those documents are concerned mostly with artificial lighting, evident in the suggestion to measure illuminance at night to remove the daylighting component from assessment. Temporal sampling is not required, presumably because maintained illuminance from electric lighting systems is relatively constant over time.

The clear emphasis of lighting standards on artificial lighting, although not entirely surprising coming from IES, does seem to overlook mounting evidence from post-occupancy evaluations that the most common source of dissatisfaction with the lighted environment is a lack of daylight (e.g. Abbaszadeh et al, 2006; Al Horr et al, 2016), as well as lower lighting energy from reduced artificial lighting. Mardaljevic et al. (2009) and Osterhaus (2005) attribute this to limited quantitative understanding of what defines a well-daylit space. In response to work by Heschong (2002) and Mardaljevic et al (2009) the IES Daylight Metrics Committee published a separate document in 2012, LM-83 *Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)*, that discusses testing and calculation of daylighting performance in existing buildings. Rather than relying on measurements, both sDA and ASE are determined for operating hours on an annual basis using simulation. Yet the use of simulation rather than measurement has been deemed by some to be a major limitation of these indices (Reinhart et al 2014; Nezamdoost et al 2017).

Considering the misalignment between national standards on recommended illuminance levels, mounting evidence that occupants prefer spaces that appropriately use daylight (Galasiu & Veitch, 2006), and that simulation may not be adequate for lighting performance assessments, continuous monitoring of indoor illuminance with contemporaneous subjective evaluations emerge as an effective way to assess the quality of the lighted environment in premium-grade commercial offices.

2.4 Acoustics

The most prominent standard on noise in office environments is ANSI S12.2 *Criteria for evaluating room noise* (2008). It addresses background noise (e.g. Beranek, 1957 and Beranek, 1960), with particular emphasis on noise from HVAC equipment operation. It also specifies recommended maximum noise levels for different areas within an office. These thresholds are based on the A-weighted sound pressure level (SPL) given in decibels (dBA). There are two additional evaluation methods (noise criteria curves and room noise criterion), but background HVAC system noise is most relevant to low-cost, continuous IEQ monitoring systems like SAMBA.

A companion standard, ANSI S1.43 *Specifications for Integrating-Averaging Sound Level Meters,* outlines the performance requirements for sound level meters (SLM) including averaging characteristics and directionality. Most relevant to this paper are the SLM tolerance types – Type 0, Type 1, and Type 2 – that categorise instruments on the basis of accuracy under reference environmental conditions (see table 3). EN 61672-1 *Electroacoustics – Sound level meters Part 1: Specifications,* lists two performance categories. Permissible deviations in response level for different frequency ranges are given in both standards, generally widening at the low (<40 Hz) and high (>4 KHz) ends.

Table 3. Permissible tolerance limits for sound level meters specified in the prominent office acoustics standards.

ANSI S1.43	**EN 61672-1**	**Intended use**
Type 0 ±0.4 dB	-	Laboratory
Type 1 ±0.7 dB	Class 1 ±0.8 dB	Laboratory and controlled field use
Type 2 ±1.0 dB	Class 2 ±1.1 dB	General field use

ANSI S12.2 details measurement procedures through a spatial sampling routine based on measurements of maximum A-weighted SPL (minimum Type 2 device) made at a single point or an average of points near the height of either standing or seated human ears. The European counterpart, ISO 3382-3 *Acoustics -- Measurement of room acoustic parameters -- Part 3: Open plan offices* provides a more detailed measurement protocol; at least 4 but ideally 6 ~ 10 measurements made along a transect crossing multiple workstations. Such a procedure is required because the ISO standard considers a number of speech indices such as Speech Transmission Index. For this reason, background noise level (discretised into octave bands) is measured at the workstation during work hours but without occupants.

Because standards focus more on background noise from HVAC equipment (where noise level does not vary significantly over time) and less on speech, there are no temporal sampling requirements for sound pressure level over timeframes longer than a few minutes. It seems logical to assess the acoustic performance of a building when it is unoccupied to avoid penalising simply because of noisy occupants. Yet there is mounting scientific evidence (Banbury & Berry, 2005; Kaarlela-Tuomaala et al., 2009) to suggest that speech distraction and speech privacy are the key determinants of occupants' overall satisfaction with indoor environments, particularly in open-plan offices (Kim & de Dear, 2013). Current standards do not adequately address speech stimuli due to various assumptions and simplifications that deviate from real-world talker-listener office interactions (Haapakangas et al., 2017, Yadav et al., 2017). If speech distraction and privacy are to be considered in evaluations of indoor acoustic quality, then longitudinal sampling procedures during occupied hours will be necessary. Continuous monitoring systems such as SAMBA that are equipped with more advanced acoustic measurement devices will be necessary in realising this requirement.

2.5 IEQ Guidelines

Various organisations and industry bodies publish IEQ guidelines to assist practitioners in developing monitoring and management strategies in accordance with national and international standards. They are designed to be more pragmatic than standards, and usually describe measurement protocols and equipment requirements for objective assessments of building performance. As such, they are an important source of metrological guidance for building operators. In addition, the strong emergence of IEQ rating tools as a motivator for building operators to conduct detailed evaluations in commercial buildings has served to highlight the importance of physical monitoring; these rating tools will not be addressed in this paper.

EN 15251 (2007) is an ambitious attempt to harmonise the diverse components of IEQ assessments – thermal comfort, indoor air quality, lighting, and acoustics – into a single standard. Titled *Indoor environmental input parameters for design and assessment of energy performance in buildings*, its principal focus is the operation of a building and its indoor environment as it relates to building energy consumption and long-term performance evaluation. The resulting design guidelines contain normative references to related European standards, such as ISO 7730 for thermal comfort and EN 12464-1 for lighting. Greater depth and more details are provided for thermal comfort and indoor air quality evaluations than lighting or acoustics. Of particular relevance to this paper, however, is the focus on instrumental measurements and long-term monitoring of IEQ parameters to evaluate building performance and assign category ratings e.g. Category 1, 2, 3 etc, and the potential for these ratings to promote energy-intensive building management practices through their misinterpretation as indicators of built environmental quality (Nicol & Wilson, 2011).

A companion document to EN 15251 prepared by the Federation of European Heating, Ventilation and Air-Conditioning Associations is the *Indoor Climate Quality Assessment* guidebook (REHVA, 2011). Authored by members of the research community, it outlines an assessment framework for thermal comfort and indoor air quality to meet the requirements of EN 15251. An entire chapter is dedicated to the metrological considerations, with details being excerpted from other standards and guidelines. For example, thermal comfort equipment specifications are identical to those in ISO 7730, and spatial and temporal sampling procedures reflect those in ISO 7726. Measurements of relevant thermal parameters in existing buildings should be made at locations and in time frames that are deemed representative of "normal" cold and warm season conditions, but no clear definition of what constitutes representative is given. With regards to accuracy, the REHVA authors acknowledge the importance of balancing equipment costs with adequate monitoring of relevant quantities over longer time periods. However, their own sensitivity analysis demonstrates how the thermal comfort classification scheme for PMV practically mandates the use of laboratory-grade measurement equipment. Whilst the consolidation of information into a single document replete with normative language is helpful for practitioners to better understand the measurement requirements, many important details are missing for real-world implementation.

ASHRAE have an equivalent document for the U.S. context titled *Performance Measurement Protocols for Commercial Buildings* (ASHRAE, 2010). Developed in partnership with U.S. Green Building Council (USGBC) and the Chartered Institution of Buildings Services Engineers (CIBSE), the document harmonises existing measurement methods from various standards and guidelines into a standardised protocol to facilitate meaningful comparisons of building performance across all IEQ dimensions. It delineates three tiers of IEQ Performance Measurement Protocol affording different trade-offs between cost and accuracy: Basic (Indicative), Intermediate (Diagnostic), and Advanced (Investigative). Kim & Haberl (2012a,b) tested all three of these levels of PMP in a single case study building located in central Texas. Whilst the protocols indicated which parameters needed to be measured, they found that across all three tiers there was uncertainty around the measurement requirements such as sampling strategy and analytic techniques, which was further compounded by limited instruction on interpretation of results.

3. SAMBA Performance Tests

What emerges from this discussion of standards and guidelines is a cacophony of instructions on which quantities to measure, how they impact occupant comfort and health, and how they are measured using traditional metrological techniques. But there is negligible discussion of the merits and methods of continuous monitoring of building IEQ performance. Excluding low-cost monitoring systems on the basis of undesirable or unacceptable inaccuracies may be couched in terms of non-compliance with standards. As noted earlier, these standards and guidelines were not developed for technologies enabling continuous measurement of IEQ parameters. The research community, and subsequently the commercial building sector, have assumed these standards apply to *all* measurements based on the principle that greater accuracy is intrinsically better. The unintended consequence of this fixation with accuracy is, paradoxically, a failure to adequately characterise and document indoor environments due to the prohibitive costs of deploying laboratory-grade equipment for longitudinal monitoring of a very limited number of case-study buildings (Foldvary et al. 2018). There is a need to quantitatively assess the trade-off between instrument accuracy and representative measurement protocols that capture variability of parameters. Such an analysis will provide a rational framework for long-term evaluations of building IEQ performance.

SAMBA devices are individually calibrated before deployment in offices to ensure robustness. The following performance assessment uses this SAMBA calibration data to determine the accuracy of measurement for each parameter. Based on this analysis, a Monte Carlo simulation will use uncertainty measures for the four environmental inputs for PMV (air temperature, globe temperature, air speed, relative humidity) to determine the ability of SAMBA to correctly classify thermal comfort as a binary outcome of comfortable (-0.5 < PMV < +0.5) or uncomfortable (-0.5 > PMV > +0.5) using 3-months of observations from Sydney offices.

3.1 Methods

It is common to see the coefficient of determination (R^2) used in linear regression to assess instrument accuracy. However, this is not an appropriate uncertainty measure for calibrated devices as it does not indicate the prediction error. In contrast, the standard error of the estimate (SEE) is an absolute measure of fit and has the advantage of being in the same units as the response variable. The analysis of SAMBA performance is based on the SEE of the calibrated sensors outputs.

Calibrations were performed in the controlled environmental chamber of the IEQ Lab (de Dear et al, 2012) and designed to suit the application - measurements of various IEQ quantities within premium-grade commercial offices. As such, testing was conducted over the anticipated ranges relevant to this application rather than full sensor measurement ranges. These calibration ranges were determined by field measurements stored in the NABERS (National Australian Built Environment Rating System) Indoor Environment database. Regression analysis (either linear or polynomial) modelled the response of SAMBA sensors to the simultaneous measurements of reference instruments. Multiple linear regression was used for air speed to include temperature compensation required for thermal anemometry.

Calibration apparatus and associated data analysis tools were designed to expedite the procedure and allow for medium-skilled operators to perform the task. Whilst the complete systems are not traceable, the reference instruments used were themselves subject to routine calibration and have requisite support documentation.

3.1.1 Thermal Comfort

A small-scale wind tunnel was built to perform calibration of thermal sensors for five SAMBA devices (see figure 1). A 140mm DC fan (5-12 V, 1.68 W; DS-140-1400-PWM, Nanoxia) controlled by Pulse Width Modulation (PWM) was mounted at one end of each channel. The reference devices were five fast-response omnidirectional thermal anemometers (±0.02 m/s accuracy, 0.1 s time constant; 54T21, Dantec Dynamics) mounted near the SAMBA devices at the opposite end of the channel to measure resulting air speed at 1 second intervals. Sufficient distance between the anemometer tip and the SAMBA devices ensure limited biasing through obstruction of airflow. Air temperature and relative humidity reference data were measured (±0.3°C, ±3%; VelociCalc 9565-A, TSI) every 10 seconds at the outlets of the wind tunnel channels. Globe temperature was measured (±0.3°C; VelociCalc 9565-A, TSI) in the centre channel using a 38mm black globe ($\varepsilon = 0.95$). Based on the NABERS IE database, the calibration range was approximately 17°C to 27°C for air and globe temperature, 20 to 70% for relative humidity, and 0.01 to 0.45 m/s for air speed. Measurements were averaged over 3 minutes for a total of 27 values over the tested ranges for each parameter.

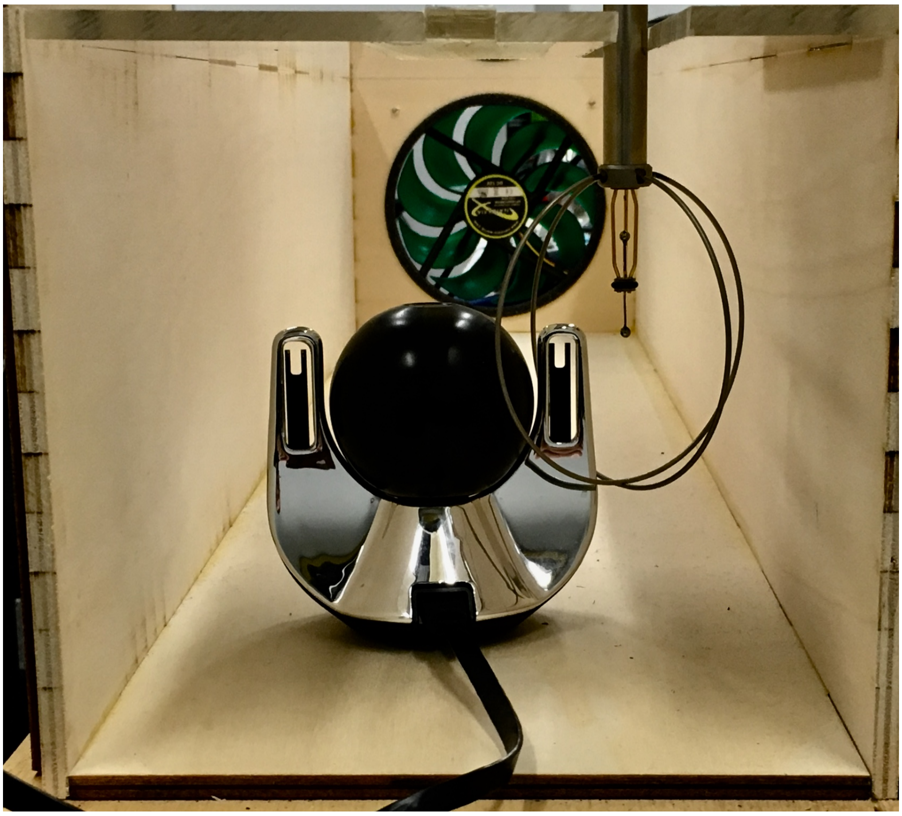


Figure 1. Purpose-built wind tunnel (81 cm x 18 cm x 18 cm) used to calibrate the thermal sensors in SAMBA

3.1.2 Indoor Air Quality

The indoor air quality sensors are calibrated by co-locating SAMBA with the reference instrument in a sealed chamber (79 cm (l) x 19 cm (w) x 19 cm (h)) with an intake port, mixing fans, and an exhaust port. The test chamber's materials were tested to ensure that off-gassing would not bias the calibration. References gases for each IAQ sensor were supplied through the chamber intake port until the desired maximum concentration was reached inside the chamber, at which point the supply vent was closed and the mixing fans were started. Concentrations were held at fixed values for a period of time before exhausting to a new, lower level. Reference instruments and measurement ranges are summarised in table 5. There was insufficient data for the performance assessment of the TVOC sensor as it is not equipped on all SAMBA systems.

Table 5. Information on the calibration procedure for SAMBA's indoor air quality sensors.

Parameter	Calibration Range	Calibration Points	Reference Instrument
Carbon dioxide	500 to 2000 ppm	6	TSI Q-Trak 7575 (±3% of reading or ±50 ppm)
Carbon monoxide	0.0 to 15.0 ppm	6	Fieldpiece SCM4 (±5% of reading ±1 ppm)
Particulates	0.000 to 0.100 µg/m^3	10	TSI DustTrak II 8532 (no accuracy given)
Formaldehyde	0 to 500 ppb	10	HalTech HFX205 (no accuracy given)

3.1.3 Lighting

Illuminance measurements are corrected for any scattering or attenuation by the light pipe positioned between the ambient environment and the sensor. The calibration apparatus is a dome designed to sit securely on top of SAMBA, with an RGB LED module (WS2812, Worldsemi) mounted as a point-source controlled via PWM. This approach limits the potential error from deviations in distance and angle of incidence between the point source and the sensor. Reference measurements (±2% linearity; T10A, Konica Minolta) are established after each power cycle of the RGB LED module. Illuminance is averaged over 1 minute for four values over the calibration range of 0 to 1600 lux.

3.1.4 Acoustics

An electret microphone with a two-stage amplifier and active filter samples sound pressure (SPL) at 16 kHz. A-weighted sound pressure level (dBA) is calculated using Fast Fourier Transform. The calibration procedure involves co-locating SAMBA with a reference SPL meter (Type 1; NL-52, Rion) near a monitor outputting a noise signal comprised evenly of sound frequencies distributed across the audible frequency range (100Hz – 16000KHz). Distance from the monitor and directionality to the acoustic point source are identical for the SAMBA microphone and the reference SPL meter. The microphone's mounting on the PCB means the incidence of sound will affect the SPL readings. Sound pressure level (in dBA) is averaged over 1 minute for seven values across the calibration range of 40 to 75 dBA.

3.2 Thermal comfort compliance classification

Many standards and rating tools classify the indoor thermal environment based on PMV ranges, for example the ISO 7730 "Class" categories. The specificity of such multi-class comfort categories has been challenged (Arens et al. 2010, Nicol & Wilson 2011), so compliance here will be defined by the industry-accepted binary performance criterion, namely an acceptable/unacceptable classification in which $-0.5 < \text{PMV} < +0.5$ represents the comfort range which 90% of occupants would find it thermally acceptable, while thermal conditions beyond that PMV range are deemed unacceptable for a commercial office space. When assessing office thermal comfort, therefore, the precise estimation of PMV becomes less critical than the ability of a measurement system to correctly categorise conditions as acceptable or unacceptable.

Apart from being able to accurately and reliably classify the indoor environment at a point in space and time as either acceptable or unacceptable, a robust monitoring strategy should also capture variations in the environmental conditions through time, particularly during the building's occupied hours. The ideal system would make no errors in its binary acceptability classifications (neither false-positive nor false-negative) across the full range of conditions prevailing in the space being assessed. It is on this basis that the SAMBA system is assessed – correctly classifying an indoor environment as comfortable or uncomfortable over a given timeframe.

Monte Carlo methods demonstrate the implications of a singular focus on accuracy of measuring equipment at the expense of representing the variance in the thermal environment over time. Thermal comfort data from 62 SAMBAs distributed throughout 24 office buildings located in Sydney's CBD between October to December 2017 (spring to summer) were used to define the "correct" compliance rates against which six fictitious measurement systems with varying levels of accuracy will be compared. Measurements from actual buildings were taken to be true (perfect accuracy), and a simulated sample was generated for all thermal measurements by uniformly at random choosing a point that falls within the error tolerances for that equipment. For example, the simulated sample for an air temperature measurement of 23.0°C measured by a device with ±0.5°C accuracy would be wholly within the range of 22.5°C to 23.5°C. This process was repeated 1,000 times to represent an array of devices for each measurement system, and the classification of thermal comfort compliance (compliant / noncompliant) based on PMV was calculated for each simulated sample. The compliance time was calculated for each of the 1,000 simulated devices and compared against the "true" (observed) compliance time. A simulated device was deemed to be accurate if it successfully calculated compliance time to within +-0.05 of the observed compliance. The percentage of accurate devices was then calculated over the entire sample set to determine the performance of the measurement system. In addition, the simulation was run using a varying number of points spread uniformly at random through the 3-month monitoring period to analyse the combined effect of sampling routines and equipment accuracy. The compliance time calculation was based on a limited number of sample points, ranging from a single measurement up to 1000 measurements spread evenly over 3-months. These different sampling frequencies were included for comparison to SAMBA's continuous monitoring strategy.

4. Results

This section presents the results from the uncertainty analysis for each measured parameter from the calibration data of 100 SAMBA devices, followed by the results of the Monte Carlo simulation. The implication of the results of the Monte Carlo simulation of thermal comfort classification on building IEQ assessments will be discussed.

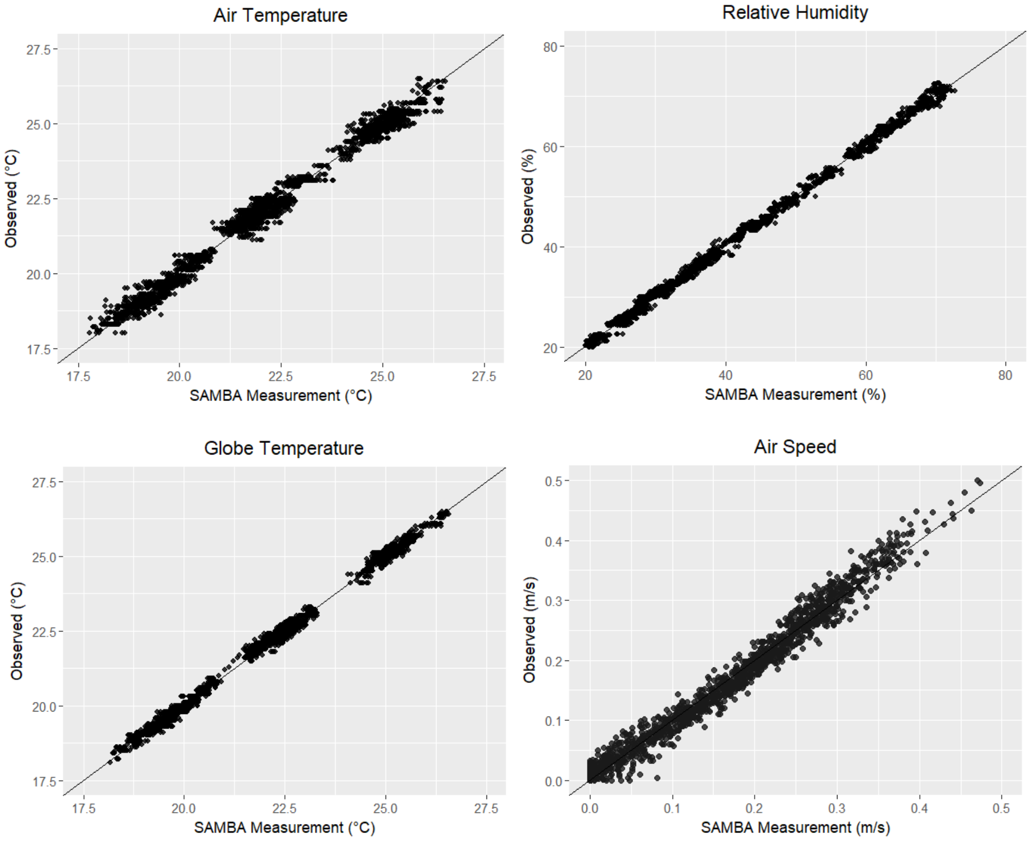
4.1 SAMBA Sensor Performance

The regression coefficients established through SAMBA calibration were used to calculate the pooled squared error based on the prediction for each SAMBA measurement paired with that of the reference instrument. The results of this uncertainty analysis are summarised in table 6, including the average standard error of the estimate (SEE) for 100 SAMBAs for each parameter, as well as the calibration range over which they were tested. Indicative costs of the instruments are included for comparison; prices listed are for SAMBAs individual OEM sensor components only and do not include required parts for signal processing, cable assemblies etc.

Table 6. The standard error of estimate (SEE) of 100 SAMBA systems in laboratory testing for each measured parameter when compared with a laboratory-grade reference device. Prices are in US dollars and approximate at June 2018.

Parameter	SEE	Range	SAMBA sensor (USD)	Reference sensor (USD)
Air temperature	0.26°C (±0.05)	18 - 27°C	\$10	\$2000
Relative humidity	1.04% (±0.12)	20 – 70%	-	-
Globe temperature	0.16°C (±0.03)	18 - 27°C	\$5	-
Air speed	0.015 m/s (±0.008)	0.00 – 0.40 m/s	\$10	\$2500
Carbon Dioxide	9 ppm (±2)	0 – 2000 ppm	\$100	\$3500
Carbon Monoxide	1.2 ppm (±0.4)	0 – 15 ppm	\$50	\$250
Particulate Matter	0.024 mg/m^3 (±0.010)	0.00 – 0.10 mg/m^3	\$15	\$5000
Formaldehyde	0.02 ppm (±0.01)	0.0 – 0.4 ppm	\$20	\$900
Sound Pressure Level	2.4 dBA (±0.4)	40 – 75 dBA	\$5	\$2000
Illuminance	8.9% (±1.5%)	0 – 1200 lux	\$5	\$1000

The uncertainty analysis suggests the performance of SAMBA sensors over the tested ranges corresponding to observed ranges in the NABERS IE database of Australian office conditions adequate to provide indicative IEQ monitoring, but perhaps not quite accurate enough for forensic applications. SAMBA measurements of thermal comfort parameters are within the recommended tolerances of ISO 7726(2001). However, the uncertainty of measurement by the indoor air quality sensors is more varied; errors in carbon dioxide measurements are relatively small (SEE 9 ppm) compared to the performance of carbon monoxide and formaldehyde sensors at low concentrations typically encountered in office environments (SEE 1.2 ppm and 0.02ppm respectively). Whilst these may not be sufficient for detailed investigations, the uncertainty measures demonstrate the adequacy of all the SAMBA sensors to detect problem areas within a building and categorise performance indicators as compliant or noncompliant. This is the desired purpose of a continuous monitoring system, and allows building operators to efficiently target IEQ issues with comprehensive follow-up measurements.



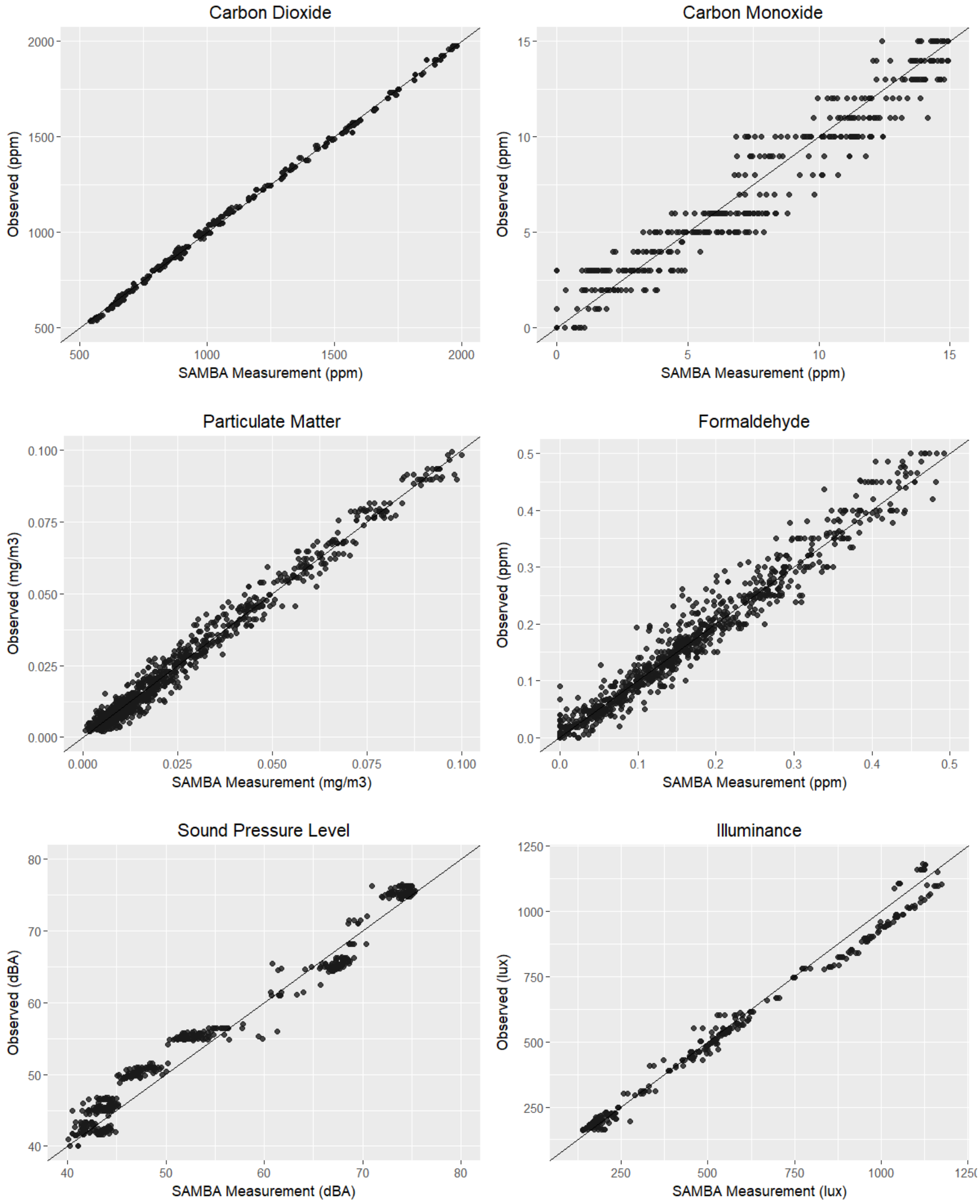


Figure 2. Plots indicating linearity in the calibrated responses of SAMBA IEQ sensors compared with measurements made by laboratory-grade reference devices.

Plots in figure 2 comparing SAMBA measurements to measurements made with laboratory-grade counterpart sensors indicate linearity of calibrated responses, with the exception of sound pressure level and illuminance. The underestimation of SPL between 45 to 55 dBA is likely due to the response characteristics of the electret microphone to different frequencies. Further calibration is required to improve linearity over the full range of interest. The overestimation of illuminance measurements above 750 lux suggests the sensor response over the tested range may be better described by polynomial rather than linear regression. But for the purposes of this uncertainty analysis, the fact that most standards set the minimum illuminance level for screen-based work at approximately 200 lux, increased measurement uncertainty above 750 lux will not impact compliance assessments of the lighted environment.

While results of the uncertainty analysis of SAMBA are encouraging for a first-generation device, the large-scale analysis presented here indicates that further improvements can be made without wholesale re-design modifications. These include changes to the calibration procedure to further reduce potential uncertainty in the reference exposure values, software enhancements to improve signal processing and goodness-of-fit for calibration of regression equations, or hardware modifications to optimise positioning of components on circuit boards or switching to newer sensors with better performance characteristics. Further improvements to system performance are achievable by inclusion of self-calibration or correction algorithms, made possible with sensor array networks, within the data analytics platform.

4.2 Thermal comfort classification

Testing the performance of sensors in real-world settings is difficult as it requires comparison of measurements to a precise reference device. The large-scale deployment of continuous monitoring systems makes this task near impossible. If the uncertainty of measurements is known, however, a Monte Carlo simulation provides a numerical solution to determining the probability of a correct measure (or compliance classification in this case). PMV values calculated in 24 office buildings were used in the Monte Carlo simulation. These represent the variability in the thermal environments found in those offices during the 3-month monitoring period. Environmental inputs into the PMV model were based on measurements from 62 SAMBA monitors. Clothing level was dynamically predicted using the method by Schiavon & Lee (2012) and metabolic rate was assumed to be a constant 1.1 met. Only occupied hours (8AM – 6PM, Monday to Friday) were considered for the analysis as other times are excluded from compliance checks. The resulting database contained over 270,000 PMV records. Figure 3 shows the central tendency of -0.2 to -0.3 PMV, towards the cool side of the compliance target zone. Of particular relevance to the present analysis are the boundaries between the zones of acceptability: approximately 10% of records are between -0.4 and -0.6 PMV and 6.5% between +0.4 and +0.6 PMV. These regions present the greatest potential for incorrect classification of thermal comfort compliance.

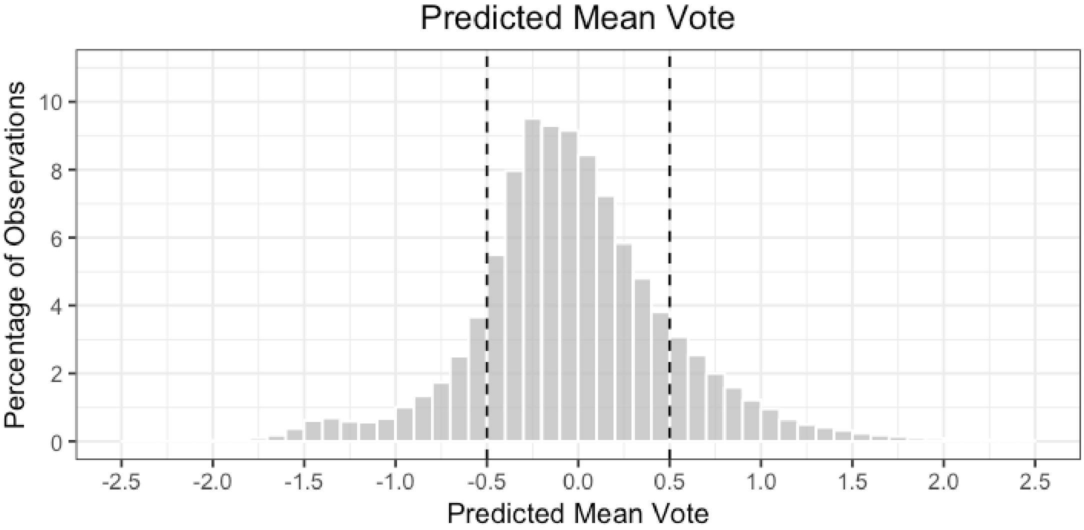


Figure 3. Distribution of Predicted Mean Vote thermal comfort index values calculated from measurements during occupied hours in Sydney office using SAMBA (n = 270,032).

The Monte Carlo simulation included six different hypothetical monitoring 'systems' with varying levels of measurement accuracy (see table 7), ranging from an ideal system with perfect accuracy through to poor-performing system with very loose accuracy tolerances. The probability of these systems correctly classifying thermal comfort compliance for the entire 3-month monitoring period was assessed across a number of spot measurements distributed evenly through time: 1, 5, 20, 50, 100, 250, 500, 1000 and 'continuous' (every 5-minutes for 3-months of occupied hours). The probabilities of correct comfort compliance classifications based on the 'continuous' measurement procedure is shown in table 7. Systems with the tightest tolerances – Ideal and ISO 7726 desirable - achieved 100% correct compliance classification based on 5-minute sampling intervals ('continuous'). SAMBA was able to correctly classify PMV compliance 94% of the time. The 5% improvement between SAMBA and ASHRAE 55 appear to be the result of greater accuracy in temperature measurements.

Table 7. The measurement accuracy for the thermal parameters of each system included in the Monte Carlo simulation of thermal comfort compliance. The last column shows the probability of each system delivering a correct classification based on a 5-minute sampling procedure.

	Air Temp (°C)	Rel Hum (%)	Globe Temp (°C)	Air Speed (m/s)	Air Speed (%)	'Continuous' Correct
Ideal	±0.0	±0	±0.0	±0.00	±0	100%
ISO 7726 desirable	±0.2	±2	±0.2	±0.02	±7	100%
ISO 7726 required	±0.5	±3.5	±0.5	±0.05	±5	93%
ASHRAE 55	±0.2	±5	±0.2	±0.05	±0	99%
SAMBA	±0.5	±3	±0.5	±0.05	±0	94%
Worst performing	±1	±10	±1	±0.1	±10	49%

It is unsurprising that the "Ideal" and "ISO 7726 desirable" systems achieved 100% correct classification of the PMV database using 5-minute measurement intervals. But clearly it would not be feasible to permanently deploy laboratory grade equipment to measure the thermal environment for the sole purpose of determining long-term comfort standard compliance. Even though the performance of these systems is excellent, their application in the assessment of long-term thermal comfort compliance of an office building is necessarily based on a handful of spot measurements. In contrast, SAMBA was designed for autonomous operation and permanent *in situ* deployment. Therefore, the comfort compliance performance of an office building by a system such as SAMBA can be based on the totality of continuously measured data rather than just spot measurement.

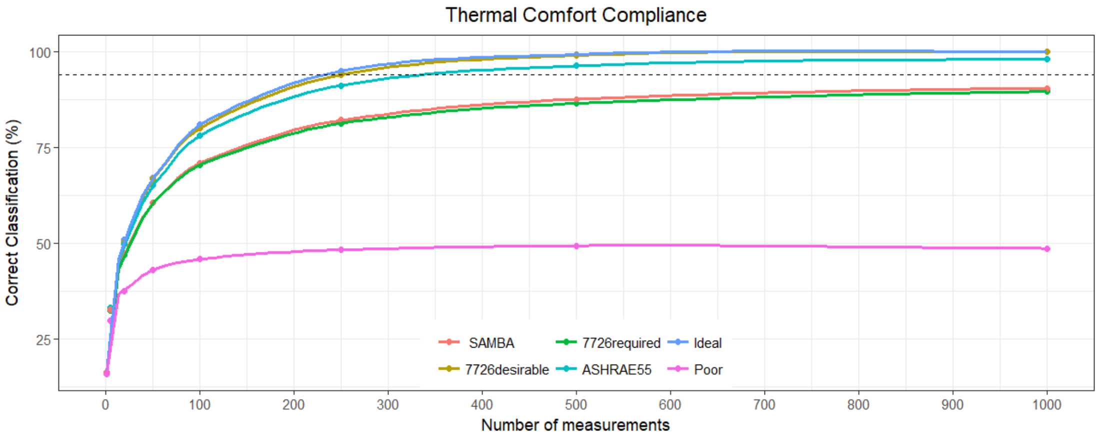


Figure 4. Correct thermal comfort classification of different grades of measurement system for different sample sizes of measurements. The dashed line at 94% corresponds to the overall probability of a correct classification of SAMBA based on all measurements (sample size = 7320 for 3 months of occupied hours).

The different grades of instrumentation included in the Monte Carlo simulation allow quantitative assessment of the trade-off between representation of variability in the thermal environment, sampling frequency, and instrument performance. The results in figure 4 show much lower probabilities of a correct classification of thermal comfort performance for the entire monitoring period when basing it on smaller samples of measurements. This is not surprising considering the thermal environment of an office varies over time and is likely to switch between compliant and noncompliant. When the comparison is based on measurement uncertainty as well as sampling protocol, the performance outcomes are even more differentiated than being based on just instrument accuracy. The three systems that out-performed SAMBA in their continuous correct classification – "Ideal", "ISO 7726 desirable", "ASHRAE 55" – reached 94% probability on fewer measurements. However, the sample size required for the ideal and "ISO 7726 desirable" systems to match SAMBA's level of performance is approximately 250 spot measurements. Expressed another way: 250 samples of a typical office environment, evenly spaced throughout a 3-month monitoring period, would be required to achieve the same level of confidence in long-term thermal comfort compliance classification as a continuous monitoring system with less-precise but acceptable measurement uncertainty. This equates to a spot measurement made every 2.4 business days. For ASHRAE 55 requirements it is closer to 350 samples, or one every 1.7 business days in the 3 -month monitoring period.

Variations in thermal conditions occur on diurnal timescales as well as synoptically, seasonally, and annually. It is therefore possible to capture one component of variance in comfort conditions over a single day rather than the entire 3-month period. However, the likelihood of achieving 94% confidence on long-term comfort assessments using a random one-day measurement strategy is very low. Given that annual variance in indoor conditions is likely to be greater than that observed within a 3-month sampling period, it becomes difficult to justify the use of one-day spot measurements for the purpose of long-term comfort compliance assessment. Yet this remains the approach of many rating tools in use across the buildings sector, on the basis of a mistaken belief that greater accuracy is inherently superior. Whilst there is lower confidence in individual classifications, there is significantly greater confidence in long-term compliance diagnoses made by continuous monitoring technologies. Perhaps it is for this reason that ASHRAE 55 makes allowances for less accurate BMS data in comfort assessments.

Alternative sensing technologies provide a fairer assessment and rating of a building's indoor environmental quality and afford significantly greater opportunity to enhance our understanding of building dynamics. Spot measurements with laboratory-grade equipment are still necessary for forensic investigations of thermal environments i.e. when there are numerous complaints of discomfort emanating from a particular zone in a building or when tenants are challenging their landlords, so this diagnostic strategy will remain for the foreseeable future. However, continuous or 'indicative' monitoring, as described in this paper, is better at identifying indoor environmental quality problems, allowing building operators to efficiently target resources to remediate performance issues. Spot measurements and continuous monitoring should not be regarded as mutually exclusive options but as complimentary. Comfort and IEQ standards need to outline a measurement framework that accommodates both strategies to maximise their strengths rather than precluding indicative monitoring on the specious grounds of deficient sensor accuracy.

5. Conclusion

This paper showed that the accuracy of an instrumental measure is of lesser importance to understanding building performance than characterisation of long-term variability in common IEQ parameters. To date, the well-intentioned desire for true and precise measurement may have impeded a better understanding of indoor environmental dynamics by precluding applications of low-cost continuous monitoring technologies. Instead of demanding tight tolerances in equipment performance specifications, attention should be directed towards better understanding how continuous IEQ monitoring systems can best be used within (or side-by-side with) the conventional approaches to IEQ performance assessments that evolved specifically for in situ spot-measurements. It was argued that low-cost pervasive monitoring technologies like SAMBA, a demonstrably scalable solution to comprehensive audits of building performance, can improve our quantitative understanding of, and response to, indoor environmental quality issues.

There is currently a dearth of guidance on sampling procedures or measurement protocols to ensure fair and reliable representation of measured IEQ parameters. What is the density of sensors needed to capture spatial inhomogeneity across a building floor plate, and over what timeframe should measurements be conducted to ensure an appropriate level of variability is captured? Furthermore, there is little discussion of the most robust analytical techniques for time-series IEQ data, how to integrate spatial and temporal measurement sites within an air conditioning zone, floor, or building, and how to effectively visualise and communicate the large volumes of IEQ data resulting from ubiquitous monitoring strategies. These are fertile topics for future research endeavours.

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