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Design and validation of a low cost indoor environment quality data logger

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Abstract: The appraisal of indoor environment quality in residential dwellings presents a range of technical challenges. Indoor environment quality (IEQ) is often described as having thermal, visual, aural and olfactory dimensions, each of which is assessed subjectively by the resident. While it is possible to objectively assess physical parameters relating to each aspect of IEQ, either directly or indirectly, resident satisfaction with the environment is determined subjectively so must be inferred. In the field study of thermal comfort (FSTC) approach, objective physical measurements are collected simultaneously with resident preference and sensation information, usually via a diary or written survey. This research paper explores a new approach to residential IEQ appraisal which extends the FSTC approach to the visual, aural and olfactory dimensions using a low cost data collection system based upon the Arduino microcontroller platform. The paper describes the design developed, presents early validation results and draws preliminary conclusions.

Keywords: IEQ, Data Logger, Arduino, Microcontroller, Occupant perceptions

1. Introduction

Indoor environments which satisfy the needs of building occupants are an important goal of building designers. Understanding how buildings actually perform in this regard is likely to be an important pathway to developing improved designs in future. One such technique for evaluating the performance of existing buildings, of which the indoor environment is an element, is the Post Occupancy Evaluation (POE) (Baird et al., 1996; Nicol and Roaf, 2005). While such studies can provide important information as to the established views of building occupants they often require additional environmental data to interpret. Theory building which links building attributes to occupant perceptions is not possible from survey data alone, as the referent environmental conditions which may contribute to survey responses are missing. This is problematic from a building design standpoint as survey outcomes lack the requisite physical environment information needed to make them actionable. This paper will investigate a data collection approach which overcomes this shortcoming by integrating the collection of occupant satisfaction data and indoor environment data using a single logging device.

2. Background

A 'multi-sensory' approach (Dubois *et al.*, 2007) is often applied when undertaking building evaluation. POE studies frequently consider occupant satisfaction across dimensions which could be considered as sensory, while also addressing factors that could be 'occupant' or 'occupant need' related (Preiser, 1983). With the exception of the occupant's assessment of 'overall comfort', temperature, air, light and noise are commonly used to describe indoor environments in buildings and form the structure of POE survey's such as the Building User Survey (BUS) (Leaman, 2010).

Lai *et al.* (2009) describe evaluation of Indoor Environment Quality (IEQ) in residential buildings as having four components: thermal comfort, Indoor Air Quality (IAQ), visual comfort and aural comfort. Evaluation of the components of IEQ can be undertaken by employing approaches similar to those used to assess thermal comfort, whereby occupants are asked to assess the environment they experience while at the same time physical parameters such as temperature are collected, enabling models to be developed relating inhabitant assessments to environmental outcomes (Lai *et al.*, 2009).

Differences between the POE approach and the Field Study of Thermal Comfort (FSTC) approach are described by Nicol and Roaf (2005, p. 339):

> One important difference between a POE of a building and an FSTC is that whereas the former is concerned with the performance of the building, the latter is more concerned with the responses to a building (or other environment such as a vehicle or out of doors) of its occupants. In the POE, the occupant provides a subjective measure of a building and acts effectively as its 'memory' (so that questions are in a form such as 'how often is the building hot in summer?')…In the FSTC the occupant reports on his or her own feelings at the time of the survey ('I feel hot now'). (Nicol and Roaf, 2005, p. 339)

An advantage of the FSTC approach described by Nicol and Roaf (2005) when seeking to understand occupant satisfaction is that it enables a connection between satisfaction and objective environmental variables and behaviours to be established. The connection is useful as it allows for the possibility of a model to be built linking environmental parameters to expected satisfaction or dis-satisfaction of occupants.

Collection of both occupant and physical environmental data can be undertaken using logging equipment, an approach which many thermal comfort and some IEQ studies have employed in the past. A common and reliable approach is to employ time-stamped paper surveys to collect occupant data which are later synchronised with time-stamped environmental data which are often collected using multi-channel electronic logging equipment such as the HOBO U12-13 (Daniel *et al.*, 2014). Alternatively, occupant data can also be collected using electronic loggers which simplifies post processing activity as surveys do not need to be keyed and in some cases data is automatically synchronised with environmental measures (Williamson *et al.*, 1989). Opportunities to collect occupant subjective data electronically have become more practical as smart phone technology has become widely available, as illustrated by the approach employed by Saman el al. (2013).

3. Application requirements and constraints

The following section outlines the main objectives of the proposed logger designed to survey IEQ. At the outset, it is recognised that in seeking to parametrically characterise IEQ a reduction of occupant experience is being undertaken. The usefulness of the resultant parameters are limited and require considered interpretation in concert with the perceptions of the occupant. Adopting the four domains of IEQ commonly described, Bluyssen (2009) identifies a list of parameters in each domain (Table 1).

Table 1: IEQ parameters of interest. Adapted from Bluyssen (2009, p. 7).

Thermal Comfort	Lighting quality	Acoustical quality	Air Quality
Temperature (air and radiant) Relative humidity Air velocity Turbulence intensity Activity and clothing	Luminance and illuminance Reflectance(s) Colour temperature and colour index View and daylight Frequencies	Sound levels(s) Frequencies Duration Absorption characteristics Sound insulation Reverberation time	Pollution sources and air concentrations Types of pollutants (allergic, irrational, carcinogenic, etc.) Ventilation rate and efficiency

Ideally, a characterisation of the indoor environment would address each of these parameters, however this is likely to be technically challenging. It is, however, possible to select a range of parameters from within this group which are likely to be assessable using readily available sensors and a data logger.

The accuracy of measurements undertaken needs to be understood when interpreting results from the data logger. When undertaking basic measures of the environment important rules regarding instrument accuracy have been established when assessing thermal comfort and other domains of IEQ. For a selection of likely measures, recommended accuracies have been compiled in Table 2. Accuracies have been drawn from the thermal comfort literature and documentation provided with measurement equipment which is commonly used in industry for the said purpose.

Table 2: Desired accuracy of sensors.

	Range	**Accuracy**	**Source**
Air temperature	10 to 30 Deg C	+/- 0.2 Deg C	ASHRAE Std 55 - 2013
Mean Radiant Temperature	10 to 40 Deg C	+/- 1 Deg C	
Air velocity	0.05 to 1 m/s	+/- 0.05 m/s	
Humidity	0 to 80%	+/- 5% RH	
CO2 concentration	0 to 10000 ppm	+/- 75 ppm + 3 % of measured value (to 5000 ppm)	Testo IAQ Probe (Testo 480 family)
Illuminance	0 to 100000 Lux	Class C according to DIN 5032-7	Testo Light Probe (Testo 480 family)
Sound Level	30 to 130 dBA	+/-1.0 dBA	Testo 816 Sound Level Meter

In addition to physical parameters, a logger must be able to collect the subjective occupant assessment of the environment. In the FSTC approach it is common to employ accepted categorical scales for this purpose, comprising up to seven points (such as the ASHRAE and Bedford scales described by McIntyre (1978)). It is also common to incorporate free-form responses to open ended questions, especially where paper based surveys are employed (Daniel *et al.*, 2015). The number of survey questions used in a longitudinal study employing a FSTC approach is likely to be small as it is recommended that such surveys be kept as simple as possible (Nicol *et al.*, 2012).

Minimising disruptions to normal household activities and avoiding "subject fatigue" (Nicol *et al.*, 2012, p. 115) are also important considerations in the design and installation of any logging devices. Any logging device placed into the home needs to be small enough to enable participants to locate the device for convenience while at the same time achieving the measurement goals of the researchers. Survey instruments, too, must be quick and easy to use, yet clever enough to avoid habitual participant responses.

Once collected, data need to be stored securely and reliably in a manner which reduces disruption to research participants. In a residential setting, longitudinal studies can be undertaken for extended periods for up to a year in duration (Williamson *et al.*, 1989). A logger should be able to retain collected data for as much of this period as possible. A period of six months, which many commercially available temperature and humidity loggers achieve, is considered an appropriate minimum duration. Reliability of storage may also be improved if data are communicated regularly to the researcher. Telemetry of this nature highlights any data collection problems in a timely fashion allowing timely rectification. Close to 'real time' data collection may also enable a more agile data collection approach which adapts to changing study events and allows study methods to evolve as knowledge grows.

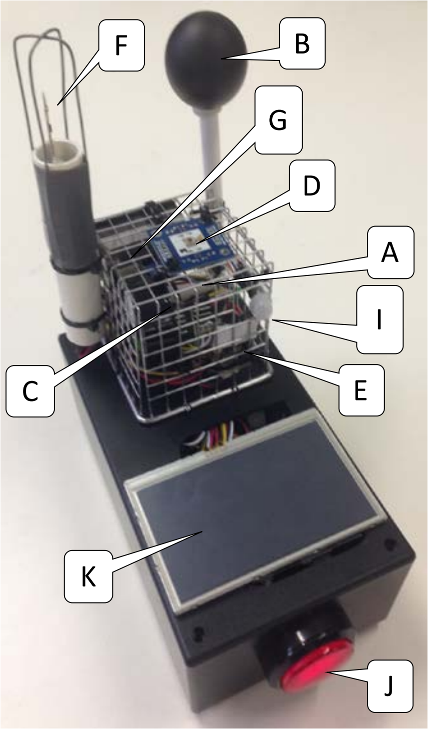
Consistent with the principle of minimising participation burden, particularly in longitudinal residential studies, the logger should be able to operate autonomously for as long as possible. In a residential setting, powering the logger from mains power is to be avoided as it introduces problems of participant compensation for electricity used and the potential for problems if the electricity supply is interrupted. Battery life should therefore be able to support the six-month data retention periods described above.

Lastly, it is important that the logger be able to be constructed from readily available components at a reasonable cost. As commercially available temperature and humidity loggers can be purchased for approximately AU$100-200, a budget of AU$500 is proposed as an objective. This budget would not include assembly which is assumed to be undertaken by the researcher and assistants.

4. Logger design

The logger design developed is based upon an Arduino Mega micro-controller board (Arduino, 2016). The Arduino Mega is selected to coordinate measurements and manage data as it is well supported and has a vibrant on-line community, dedicated to solving the many technical challenges associated with its application. Of the many forms of the Arduino microcontroller board available, the Mega is selected because of its large array of input output ports which allow the simultaneous connection of many different sensors. A downside of the Mega is that it is not designed for low power applications, making it not suited to extended operation under battery power. This problem and a proposed solution are discussed further below. Importantly, the Arduino Mega employs a simple and easy to learn programming language based on the Processing language (Fry and Reas, 2014).

One of the great strengths of the Arduino microcontroller is that many boards can be enhanced through the addition of 'shields'. One such shield, the Grove Mega Shield by SEEED Studio, is designed specifically for the Arduino Mega board, providing for 21 standardised four-wire ports for the connection of sensors. The arrangement facilitates the robust connection of sensors two the Arduino-Mega board and allows for standard sensors which are available pre-wired to be easily connected.



Key	Measure	Sensor manufacturer and name	Description	Accuracy
A	Air temperature	Maxim Integrated, DS18B20	Semiconductor temperature sensor employing band gap principle. Mounted beneath radiation shield.	+/- 0.5 Deg C
B	Globe temperature	As above	As above, however is mounted within 40mm black ball.	+/- 0.5 Deg C
C	Relative humidity	Sesirion, SHT21	Capacitive relative humidity sensor.	+/- 2 %RH
D	Light intensity and colour	TAOS, TCS3200	Array of photodiodes, some of which are placed under red, blue and green filters. Provides measures of clear, red, blue and green light.	not stated
E	Sound level and frequency	DF Robot, Sound analyser	7 band filter based on MSGEQ7 processor. Provides amplitude of sound when filtered through each of 7 bands.	not stated
F	Air velocity	Modern Device, Wind Sensor rev P	Low cost anemometer employing the hot-wire principle.	~+/-0.5 m/s Prohasky &Watkins (2014)
G	Particles in air	SHARP, GP2Y1010AU0F	Optical dust sensor. Uses infrared light emitting diode and receiver to sense light reflected by particles	not stated
H - not shown	CO2 concentration	Winsen Electronics Co, MHZ16	Employs Non Dispersive Infra-Red (NDIR) principle to measure CO2 concentration.	+/- (50ppm +5% measured value)
I	Occupant presence	Manufactured in China. Unbranded.	Motion sensor employs infra-red sensor to detect motion.	3 to 5m range within zone
J	Vote button	Momentary switch	Momentary switch	not applicable
K	Touch screen	Excamera, Gameduino 2	Resistive touch sensitive screen and graphics processor	not applicable

Figure 1: Data logger prototype and sensors.

Sensors are selected for the logger which address each domain of IEQ described in Table 1. Where possible, digital sensors are selected as this simplifies connection with the Arduino-Mega. For example, Maxim Integrated DS18B20 sensors are selected for temperature measurement (both air and globe) as they contain on-board sensing and analogue to digital conversion (ADC) systems. This simplifies hardware aspects of connection to the Arduino Mega versus analogue components such as a thermistors or thermocouples which are both likely to require additional components to match effectively to the Arduino's internal ADC. The digital approach is possible for temperature, humidity, and CO_2 sensors all of which employ serial interfaces for communication with the Arduino.

Light, particles and occupancy behaviour sensing employ a slightly different connection approach, however these sensors too can be characterised as digital. The light and particle sensors employ Pulse Width Modulation (PWM) to communicate their measurements with the Arduino Mega. This approach involves varying the duration of digital output pulses to indicate a measured quantity (such as light intensity) which are timed by the Arduino Mega. These durations are then represented as measurement outcomes for each sensor. The occupancy sensor is even simpler, indicating a digital 'high' value when motion is sensed within the field of view.

Two sensors selected, the air velocity sensor and the sound sensor, use the Arduino Mega's ADC directly. The air velocity sensor employs the same principle used in hot-wire anemometers to measure air movement. As air flows over the sensor it cools a resistive element, changing its resistance and therefore the current flowing through it. The sensor requires a dedicated power supply for this purpose and generates a voltage output signal which is proportional to the velocity of air flowing over the sensor. The signal is then converted to a measurement value by the Arduino Mega's internal ADC. The sound sensor also employs a single channel of the Arduino Mega's ADC which it uses to communicate sound intensity in each of seven frequency bands. The sensor is digitally synchronised by the Arduino using a dedicated software library.

These chosen sensors are arranged into the logger as shown in Figure 1. Accuracy and measurement principles for each sensor are also shown in Figure 1. When selecting sensors cost is an important consideration which is typically traded off against accuracy. Sensors selected represent the best 'value' when it comes to cost and accuracy.

In addition to sensors, a number of other components are also connected to the Arduino Mega. First among these is the touch screen used to collect subjective observations from the building occupant(s). A touch screen is selected for this purpose as it appears to overcome a number of problems apparent with other approaches. When collecting information from the occupant, it is possible to employ alternative technologies such as the use of Smart-phones or tablets (Saman *et al.*, 2013). Smart-phones have the advantage of typically being owned by occupants so don't need to be provided by the researcher and are good at collecting information. A downside of Smart-phones is that there are a range of platforms in current use, making development of data-collection platforms a significant hurdle. Data collection platforms that use generic software infrastructure such as web-based applications (for example Qualtrics) overcome this problem, however they often lack functionality such as the ability to push survey requests to study participants. Coordination between logger and Smart-phone also becomes a challenge particularly if votes are required under particular environmental conditions. In consideration of these issues the simplest approach appears to involve adopting an 'on the logger' data collection approach, similar to previous studies (Williamson *et al.*, 1989; Chan *et al.*, 1999; Daniel *et al.*, 2014), in this case employing a touch screen rather than dials or vote buttons.

Other devices connected to the board include a battery-backed Real Time Clock (RTC) for time stamping data and a 2.4 GHz radio for communicating with remote sensors. Remote sensors are based on an Arduino derived design (Devduino distributed by SEEED Studio) which are capable of measuring a limited (three) number of sensors remote to the data logger within a 50m range. These sensors provide for the capability to measure occupant adaptive responses such as opening of windows or changes to heating and cooling device settings, or other data of interest.

To communicate data in real-time (or close to real time) a 3G cellular modem is incorporated. This modem requires a Subscriber Identification Module (SIM) card, identical to those used in mobile phones, giving the data logger a phone number and a phone account which can be pre-paid. This identity makes it possible for the logger to send data over the cellular network as real-time data points or as a pre-formatted Comma Separated Value (CSV) file which is posted to a File Transfer Protocol (FTP) account.

The last device connected to the Arduino Mega is the power controller which is needed to achieve an extended operating time on battery power. The power controller is a separate device which is based on an Arduino Pro Mini microprocessor which can switch the Arduino Mega off to save power. Typically, the logger draws approximately 300 mA of current, on average, and it is expected that this can be further reduced to 200 mA by carefully switching off sensors until they are required for a measurement. At 200 mA continuous load, battery life is still only 1.9 days so further power optimisation is required. By switching the Arduino Mega and sensors off between samples, power consumption is significantly reduced. Battery life under this approach is estimated at 160 days (sampling every thirty minutes) with more work being undertaken to increase this period.

Software for the logger is written in the Arduino Integrated Development Environment (IDE) which is based on the Processing language (Fry and Reas, 2014). Although the authors have had some basic programming experience, the language is effectively self-taught and is easy to learn. The resultant code builds heavily on work completed by the Arduino community who have invested significant effort in developing libraries and algorithms needed to operate the sensors and devices incorporated into the logger design.

Mounting the micro-controller, sensors and touch-screen present significant challenges. The objective of a logger that can be employed in a residential environment necessitates a small footprint, making packaging extremely challenging. A laser-cut screen bezel is also added to retain the touch screen and hide the rough edges of the hole cuts underneath. The battery for the logger is moved from within the box to underneath the device to improve access and allow easy checking of charge status (not shown in Figure 1).

Overall the total material cost of the logger is A$531, excluding the seven hours required to assemble it. The most expensive components are the CO_2 sensor (A$138), the touch screen (A$82) and the cellular modem (A$42). When compared to the reference equipment, the Testo 480 series IEQ kit which costs approximately $14,000 to purchase, the logger cost is remarkably small.

5. Early results

In order to undertake a preliminary assessment of the logger's measurement performance two types of test approach are adopted. The first involves placing the logger and a reference instrument into the same environment and assessing differences in measurement outcomes. The second involves subjecting the logger to known stimuli and subjectively assessing the range of resulting measurements.

In the first test the logger and a reference instrument are placed in a small (3m x 3m) office over a 20 hour period in June and the results are recorded. The reference instrument is a Testo 480 logger connected to a hot wire anemometer probe; an IAQ probe capable of measuring CO_2 concentration, air temperature and humidity; a 150mm globe thermometer; and a plane illuminance light sensor (the instrument was last calibrated in 2013). The reference logger samples the environment at 1 minute intervals. A smoothing algorithm is applied to apparently noisy sensors which involves averaging 50 readings over a 5-10 second period (air velocity, sound, particles). All other sensors are recorded without averaging. Both loggers are synchronised so that results could be compared based on internal time stamps.

Results for the air temperature and globe temperature tests are shown in Figure 2 and Figure 3, respectively. Both figures show the logger to be capturing variation in the temperature well although an offset exists in both cases. The air temperature measurement of the logger reads a value almost one degree higher than the reference instrument. This offset is found to vary in response to air velocity, reducing to almost zero at air velocities over 1 m/s which may suggest that the sensor is being heated by circuitry within the enclosure. The globe temperature variation is smaller and does drift a small amount. The comparison shown in Figure 3 adjusts the reference instrument globe temperature by approximately + 0.2 degrees (based on Humphreys (1977)) to allow for the smaller globe size of the logger (reference instrument 150 mm; logger 40 mm). Further testing in higher radiation environments will be required to prove the accuracy of this sensor.

The results of air velocity measurements are shown in Figure 4. The sensor is shown to be relatively insensitive at velocities under 0.15 m/s. Further testing has shown good differentiation of velocities over 1 m/s, however below 0.5 m/s the sensor is unresponsive. This problem could be due to the non-linear calibration equation provided by the manufacturer based on wind tunnel tests at higher velocities.

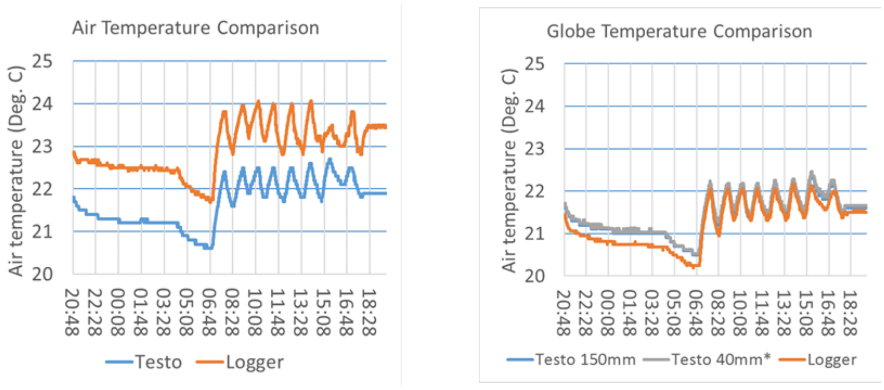
CO_2 sensor results (Figure 5) show good identification of events (people entering and leaving the room) however the sensor drifts in relation to the reference instrument. Some of this drift may be reduced by employing an algorithm to recalibrate the logger once every 24 hours. Other manufactures, including Testo who produced the reference instrument employ such algorithms to address sensor drift.

A second, less precise approach is adopted to test the more complex sensors for light colour and sound. The single light sensor on the logger contains four measurement elements, each measuring red, green, blue and unfiltered light levels. The sensor is designed for detecting the colour of objects at close range rather than the colour of ambient light. To test the sensor, it is subjected to four colours of light using an iPad screen in a darkened room (white, red, green and blue). Results for each colour detected by the sensor are recorded and their differences compared as shown in Figure 6. Results suggest good distinction of colour, however as yet lack calibration.

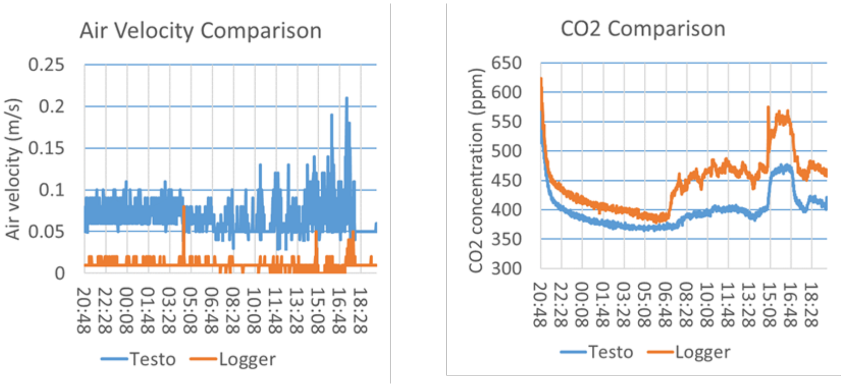
For the sound analyser a similar approach is adopted whereby a stimulus was generated and the response measured. For this sensor a signal generator (again based on iPad application) is employed to generate white noise and a range of tones. The response of the logger to each tone is recorded as is the response of a reference instrument, in this case a Testo 816 sound level meter. The Testo 816 is capable of measuring sound levels in decibels which are A-weighted to better match the varying sensitivity of the human ear to frequencies across the audible range. Results shown in Figure 7 show the logger to be most sensitive to mid-range frequencies (1 kHz to 6.25 kHz). There appears to be reasonable potential to convert the logger results to a calibrated A-weighted result in future.

6. Conclusions

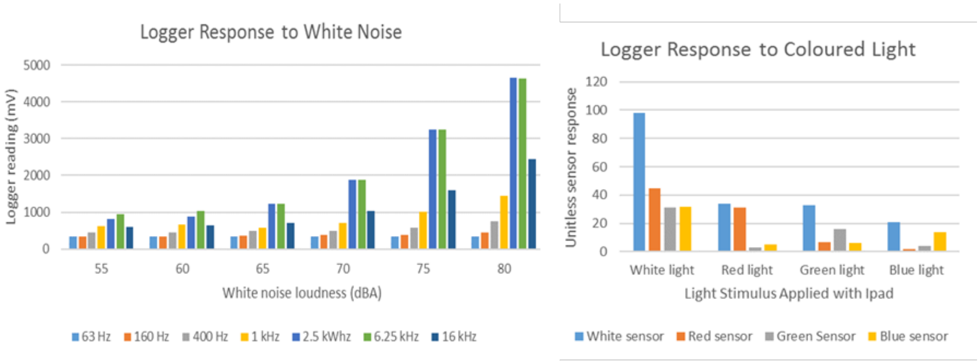
Early results have shown some differences between the logger and reference equipment however there appear to be good opportunities to reduce these differences and improve accuracy in future. The results presented reflect outcomes prior to any calibration or tuning effort, so it expected that once calibration activities are completed, accuracies will improve. With the exception of air velocity and CO_2 concentration, sensors appear responsive and suitable for calibration. Resolving shortcomings in air velocity and CO2 concentration will firstly involve altering software algorithms governing the control of these sensors, which if unsuccessful will progress to hardware alterations and lastly, sensor replacement. Further work planned will seek to reduce the differences seen in all measures with a view to deployment in a field study of IEQ in residential apartments in Melbourne.



Figures 2 & 3: Air temperature comparison & globe temperature comparison



Figures 4 & 5: Air velocity comparison & CO2 concentration comparison



Figures 6 & 7: Logger response to white noise & Logger response to coloured light

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