A cross comparison between different methods measuring environmental parameters for occupant window behaviour

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ABSTRACT
When studying occupant window behaviour in buildings, the measurement of environmental factors often requires dedicated measuring equipment. Currently, there is no universally accepted methods for the measurement, and in particular the location of sensors. Therefore, researchers more often selected the one they are most familiar with, which reduces the comparability of the collected data for different studies. This study, therefore, has carried out a comprehensive review on the existing methods used to measure significant environmental factors, such as indoor and outdoor temperatures, on occupant window opening behaviour. The study repeated different methods to measure both indoor temperature and outdoor temperature in a case study and compared the measurement results. From the analysis, it was found that the differences due to various indoor measurement methods was not quite significant, although there were obvious deviations from the reference value. Some environmental factors, such as solar gain and window opening, had greater influences and created larger differences. For outdoor measurement, the distance between the location of measured data to the case study building seemed to have significant impact. To make use of different behavioural studies as shared data base, it is recommended to develop a comprehensive standard methodology for measuring environmental factors.

KEYWORDS : Window Behaviour; Field Monitoring; Cross Validation; Influential Factor

1. INTRODUCTION
With the continued development of building science and technology, the importance of occupants' role in both energy and environmental performances of buildings has been widely acknowledged widely by researchers (Markovic et al., 2018, Wei et al., 2016, Jian et al., 2018). Within this topic, occupant adaptive behaviour has become a significant research topic, due to its contribution to both occupant comfort and building performance (Xue et al., 2014, Luo et al., 2014, Murtagh et al., 2022). According to Baker and Standeven (1996), adaptive behaviour may include adjusting clothing insulation, opening/closing windows, blinds or shading, et al.. A good understanding of occupant adaptive behaviour can help to reduce building performance gap (Darby et al., 2016, Wei et al., 2014), save building energy consumption (Yang and Wang, 2013, Ding et al., 2020) and improve occupant comfort (Luo et al., 2014, Guo et al., 2021). Within these behaviours, occupant window operation, often regarded as window opening behaviour (Wang and Greenberg, 2015), is extremely important, especially for naturally ventilated or mixed-mode buildings (Pan et al., 2019, Lai et al., 2018). Opening windows can help to adjust both indoor air quality and thermal environment (Porritt et al., 2012). In buildings with mechanical cooling/heating, opening windows may also affect the energy consumption of buildings (Wang and Greenberg, 2015). In the past several decades, studying occupant window opening behaviour has become an important research topic (Liu et al., 2022).

To study occupant window opening behaviour, field measured data in terms of occupants' window operations are quite fundamental (Qi et al., 2020, Marr et al., 2012, Liu et al., 2021). These data can be used to 1) identify the link between occupant window operation and building performance (Bekö et al., 2010, Haldi and Robinson, 2009); 2) identify influential factors on occupant window behaviour (Fabi et al., 2012, Wei, 2014), and 3) develop window behaviour models to drive building simulation (Mo et al., 2019, Jia et al., 2023). These data include the information about window operation, such as window state/angle, as well as the information on potential influential factors that are crucial (Shi et al., 2018). In existing studies these factors are classified as either environmental (e.g. indoor air temperature and outdoor air temperature) or non-environmental (e.g. time of day and building type) (Du et al., 2021, Wei et al., 2013). As most environmental factors are analogue, the data collection becomes more challenging, as researchers have adopted different methods (Wei et al., 2021).

To guide future studies in occupant window behaviour, this study has reviewed the existing methods that researchers have adopted to collect major environmental parameters and compared their results using a case study. This practice provides valuable evidence in terms of the comparability of data collected data between various studies using different methods, which is very important for cross-validation of window behaviour models.

2. REVIEW OF EXISTING ENVIRONMENTAL DATA COLLECTION METHODS

In existing studies, both Wei (2014) and Fabi et al. (2012) have reviewed the potential environmental factors of occupant window opening behaviour in buildings, such as indoor and outdoor temperatures, wind speed and CO_2. In these factors, outdoor temperature and indoor temperature have been widely accepted as the most important factors and have been commonly used for modelling window opening behaviour (Wei et al., 2013, Yun et al., 2012, Pan et al., 2018). This study, therefore, has selected these two parameters, one indoors and one outdoors, to compare the measured values by different methods.

In existing studies, outdoor temperature was commonly monitored and recorded from professional weather stations with standard built-in temperature sensors. The weather station locations, however, may be different from the case study building. Most studies set up a weather station on the roof of the building under investigation to collect local meteorological information (Wei et al., 2015, Pan et al., 2018, Shi et al., 2018). Some studies, however, chose 'nearby' public weather stations and the distance between the weather stations and the case study building could range from 280m (Bruce-Konuah, 2014) to 23 miles (37km) (Offermann, 2009).

The collection of indoor temperature was mainly done by laboratory standard temperature sensors, such as thermocouples (Hellwig et al., 2008), thermistors (Wei et al., 2013) and PT100s (Naspi et al., 2018), which have to be calibrated prior to the measurement (Tong, 2001). The locations of these sensors inside the building are not consistent among different studies, and researchers have adopted their own methods. Many researchers, such as Haldi and Robinson (2009) put the sensors near the workstations of the occupants. Wei et al. (2013) put temperature sensors under occupants' desks at the abdomen level to avoid direct sun light. Yun and Steemers (2010) made their measurement at two different locations, i.e. one on the workstation and another on top of book shelves, and used the average value of these two sensors for their analysis. Chen et al. (2020) did the measurement at the centre of the monitored environmental zones, and Stazi et al. (2017) selected the height as 1.1m above the ground. Hellwig et al. (2008) measured indoor temperature at four heights, namely 0.1m, 0.6m, 1.1m and 1.7m, complying with the recommended heights by ISO 7726 standard. In the study carried out by Pan et al. (2018), the sensor was placed on a platform at 1.8m height from the floor. In an open-plan office, Zhou et al. (2018) measured indoor temperature on a shelf, which has a height of approximately 1.5m above the floor.

3. METHODOLOGY

The aim of this study is to investigate how the different measurement methods of influential environmental parameters of window behaviour will affect the consistency between various existing datasets, providing guidelines for cross validating the existing window behaviour models. Therefore, the researchers in this study have repeated the existing monitoring methods of both indoor and outdoor temperatures, as reviewed in Section 2, and has compared the consistency of data collected by these methods.

3.1 Case Study Building and the Monitored Zone

The building under investigation is a typical office building, located in Campus B, Chongqing University, Chongqing, China (29.5672° N, 106.4597° E), as shown in Figure 1. It consists of many offices, located mainly on the south and north facades. The monitored zone a cellular office (3m width and 4m long) on the south facade, situated on the 5th floor of the case study building. It is a private office occupied by an academic staff, but during the experimental period the room is unoccupied.

Figure 1. Case study building and the monitored zone

Figure 2. Sensors' location in the office

3.2 Data Collection

According to the review summary described in Section 2, seven methods used in existing studies have been used to measure indoor temperature in this study, as shown in Figure 2 and is summarised and defined in Table 1. The indoor temperature was measured with a Hobo UX100-003 data logger, with an accuracy of ±0.21ºC. The measurement was done continuously for two months, i.e. between 15th March and 14 May, to test different scenarios, such as sunny/cloudy days and open/closed windows. According to Du et al., (2021), Chongqing is in the transitional period of the year so no mechanical cooling system was used during the experiment. The measurement interval was set as 1 minute, and all sensors were calibrated against a reference sensor prior to the data collection.

Table 1. Definitions of measurement methods and corresponding references

Method	Definition	Code	References
Method 1	Under the table	M1	(Wei et al., 2013)
Method 2	Average value of workstation and shelves	M2	(Yun and Steemers, 2010)
Method 3	ISO 7726	M3	(Hellwig et al., 2008)
Method 4	At the centre of the zone	M4	(Chen et al., 2020)
Method 5	On participants' workstation	M5	(Haldi and Robinson, 2009)
Method 6	At the height of 1.8m	M6	(Pan et al., 2018)
Method 7	On the shelf and at a height of 1.5m	M7	(Zhou et al., 2018)

The local outdoor temperature for the case study building was measured by a Hobo U30 weather station located on the roof of the building, as shown in Figure 3, with an accuracy of ±0.2ºC. The station was installed 2m higher than the roof level to prevent the influence from the heat released from the building. The measurement interval was set as 1 minute. According to the aforementioned review result, the outdoor temperature was also collected from three regional weather stations with different distances to the case study building (see Figure 3). The temperature was recorded hourly at these regional weather stations, so in the later analysis, the temperature recorded by the Hobo weather station was also filtered to match these intervals.

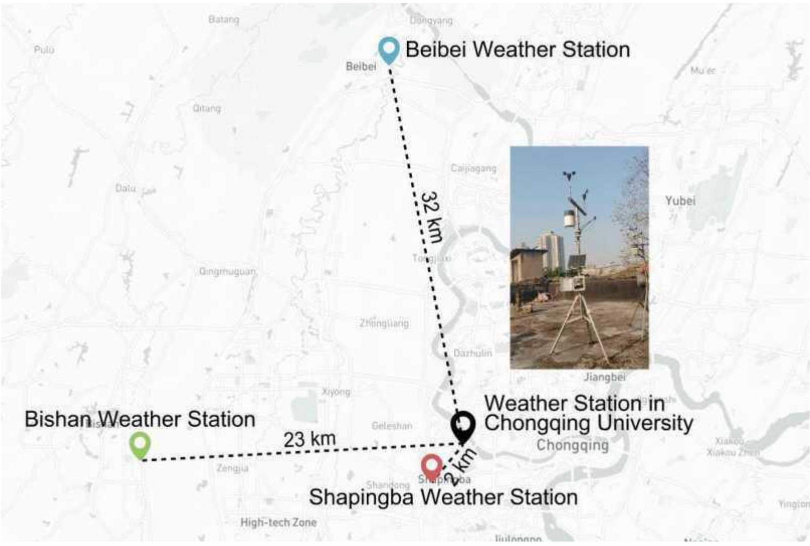


Figure 3. Measurement locations of outdoor temperature and the local weather station

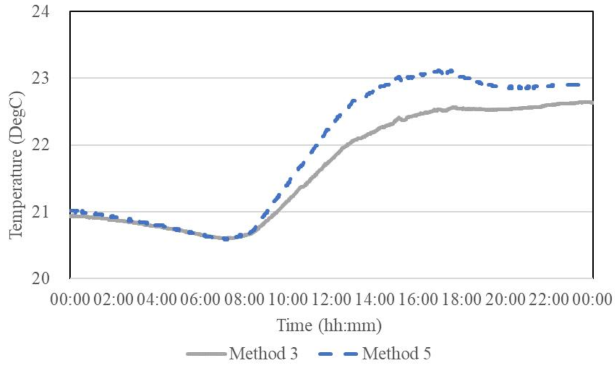
4. RESULTS AND DISCUSSIONS

4.1 Analysis of the Indoor Measurements

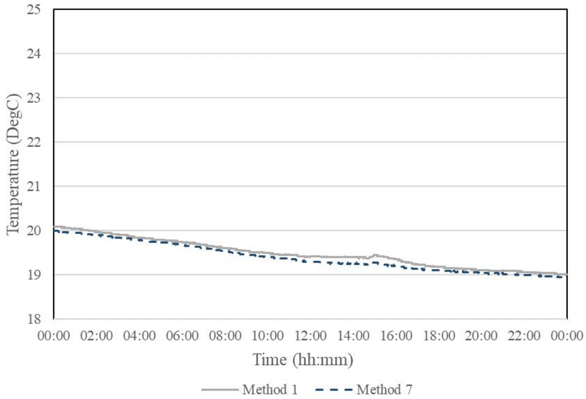
As shown in Table 1, in this study indoor temperature was measured using seven methods as was identified from current research. In the analysis, their measured values were compared to evaluate the consistency between them. To ease the comparison, the average value of all seven methods was used as the reference value, and the actual values measured by all the methods were compared individually with the average value. The summary of the main statistical values obtained from the comparison are presented in Table 2. From the results shown in Table 2, it can be seen that there is a good consistency between the measured indoor temperature using different methods, as the measured values did not quite deviate from the reference value (i.e. average value and standard deviation). In some cases, however, the deviation was as high as 2.354°C. In depth analysis also identified some factors that may increase the difference between the measured values of different methods.

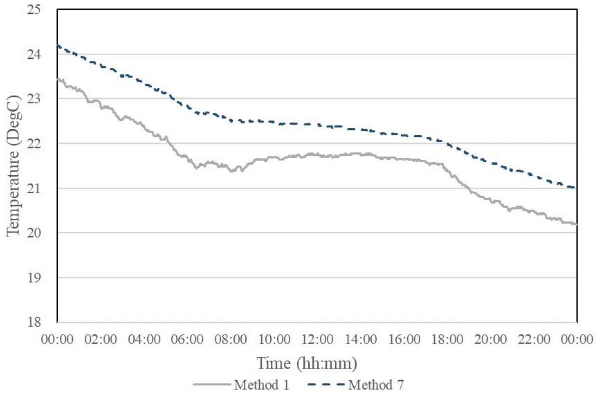
Table 2. Comparisons of measured indoor temperature

	M1	M2	M3	M4	M5	M6	M7
Average	-0.114	0.031	-0.038	-0.045	-0.009	0.079	0.096
Maximum	0.677	0.417	0.414	1.071	1.023	1.251	1.070
Minimum	-0.787	-0.775	-0.425	-0.443	-2.354	-0.184	-0.328
Standard Deviation	0.190	0.091	0.134	0.112	0.320	0.122	0.168



a: A sunny day with closed windows





b: A cloudy day with closed windows c: A cloudy day with open windows

Figure 4. Influential factors for the difference between methods

The first factor found is the availability of solar gain. Figure 4a has shown the measured temperatures using two methods, i.e. one close to the window (M5) and one away from the window (M3), on a sunny day, with the windows closed to eliminate the influence of ventilation. Clearly, during the previous night, the two values showed good consistency. During the daytime, an obvious temperature increase can be observed, making the measured value from M5 higher than that from M3. This change is much probably due to the heating effect from solar gain, which will be stronger near windows, although the avoidance of direct sunshine has been considered when deciding the location of the sensor. In this day, the maximum difference was 0.623℃, occurred at 15:00. Although this difference is not very considerable, it should be noted that the monitored zone in this study is not quite large so the sensors used for M5 are not far away from the windows. In larger rooms, it is expected that a bigger impact from solar gain will be recorded. The same phenomenon has been observed in other sunny days with closed windows as well. The second factor found is the opening of windows, which is an integral part of window behaviour studies. Figure 4b and Figure 4c show the measured values from M1 (close to the windows) and M7 (away from the windows) in two cloudy days to eliminate the impact of solar gain. Figure 4b has closed windows while Figure 4c shows open windows. Apparently, when the windows were closed, the two methods gave similar values. However when the windows were open, the values measured by Method 1 recorded much lower value than that measured by Method 7, which may be due to the local cooling effect from ventilation. Again, this phenomenon can be observed in other days to confirm the generality of the finding.

4.2 Analysis of the Outdoor Measurements

In this study, outdoor temperature was measured from four differently located weather stations. In the analysis, the measured temperature on the roof of the building was used as the reference value, against which the values collected from the other three regional weather stations, with distances of 2km, 23km and 32km from the case study building, as shown in Figure 3, were compared. In Figure 5, the measured temperatures in the week between 26 April and 2 May is shown, which demonstrate clear differences between them. In most cases, the reference temperature was higher than those measured at the three regional weather stations, may be due to the urban heat island effect as Chongqing University is located in the downtown of the Shapingba district of Chongqing city. To quantify the differences between the different weather stations, statistical values in terms of maximum and average differences and standard deviation have been calculated, as listed in Table 3. Clearly the differences seem to be significant and the further the location of the weather station the bigger the difference. This result complies with what has been suggested by Andersen et al. (2013) and Haldi and Robinson (2009).

Table 3. Comparisons for measured outdoor temperature

	Maximum Diff. (°C)	Average Diff. (°C)	Standard Deviation (°C)
Shapingba	3.74	0.54	0.64
Bishan	5.02	1.11	0.72
Beibei	5.31	1.23	0.94

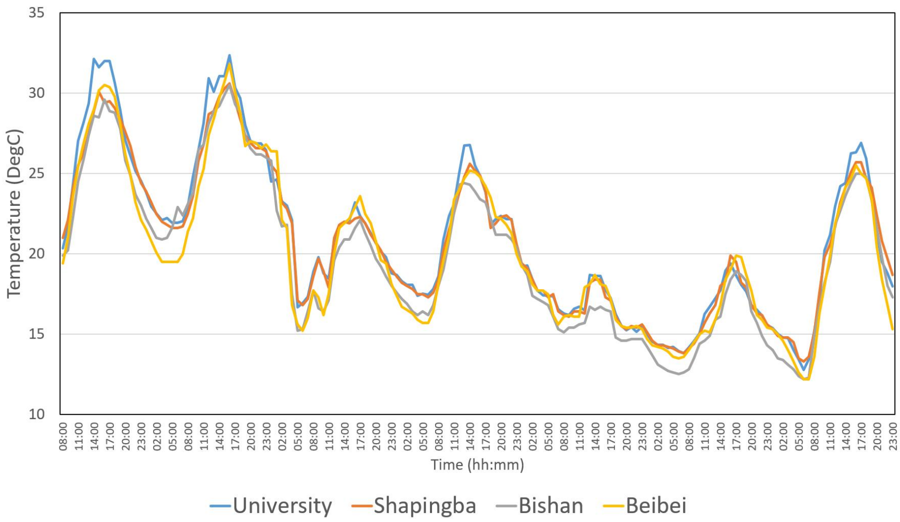


Figure 5. Measured outdoor temperatures from all weather stations (26 April – 2 May)

5. CONCLUSIONS

Occupant window behaviour has significant impact on buildings' performance. To better understand this behaviour, many researchers have conducted relevant studies, in which field data about window state/angle and related influential factors are the fundamental part of the research. In existing studies, researchers have used different measurement methods, especially for the environmental influential factors. This may cause differences in the measurement accuracy, leading to decreased comparability between the data collected from different studies. This study, therefore, has reviewed the collection methods for major environmental parameters in existing studies and applied these in a case study to compare their consistency. The main findings are as follows:

(1) The differences of indoor temperatures collected from different methods are not quite significant, with some instances larger deviation from the average, by over 2°C.

(2) Solar gain (local heating) and window opening (local cooling) may cause larger difference between data collected close to and away from windows.

(3) The distance between the outdoor weather station and the case study building showed a significant impact on the accuracy of data to reflect the local methodological condition, i.e. longer distance, larger the difference. The largest difference may go up to 5°C.

In this study, it was found that the impact from different measurement methods is not quite significant for indoor temperature. It could be due to the size of the room as in this study a small room was used. Considering that the two factors that were identified to be influential, it is expected that the difference will be more significant in larger rooms, such as an open office. Additionally, it is believed that the findings from this study will not only be useful for window behaviour studies, but can also guide studies on other behavioural types, such as blind behaviour and air-conditioning behaviour. Currently, there are still many researchers contributing in occupant behaviour studies, but until now, there is still no standard data collection method that should be used by all researchers, to enhance the confidence in cross-validation of their results. Therefore, it is suggested that a standard data collection method to be developed and implemented in relevant guidelines as early as possible for researchers to follow.

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