Real-time personal continuous monitoring of air temperature, relative humidity, carbon dioxide, and thermal and perceived air quality acceptability in Singapore

Stefano Schiavon1*, Toby C.T. Cheung2, Elliott T. Gall2, William W Nazaroff3

1 Center for the Built Environment, University of California, Berkeley, California, USA, stefanoschiavon@berkeley.edu
2 Berkeley Education Alliance for Research in Singapore, Singapore
3 Department of Civil and Environmental Engineering, University of California, Berkeley, California, USA

Abstract
Occupants’ determination of thermal acceptability (TA) and perceived air quality acceptability (PAQA) are typically analysed in climate chambers or cross-sectional field studies. Individual factors, such as expectations, environmental context, and thermal and air quality history, may contribute to the acceptability response. Fifteen Singaporean subjects participated in a 7-day longitudinal experiment in which they continuously carried a portable sensor that continuously recorded personal air temperature ($T_a$), relative humidity ($RH$) and carbon dioxide ($CO_2$) mixing ratio at 1-minute intervals. They answered several times a day an online survey about TA and PAQA, as well as providing their current location and air-conditioning status. The findings recorded acceptability ratios of over 80% at home, in restaurants and at workplaces, but not in outdoor and vehicle environments. Sample clustering by locations contributes to recognizing the patterns between acceptability and objectively measured parameters. Operating air-conditioner was positively associated with TA and PAQA at home and in restaurants. Moreover, participants who slept in air-conditioned bedrooms tended to show lower acceptability values at workplaces with uncontrollable ventilation. This longitudinal study following the same group of participants has identified the importance of location in TA and PAQA analyses with respect to physical parameter change, air-conditioning status and individual habits for sleeping ventilation mode. The database could assist in the prediction of individual TA and PAQA preference in future research.

Keywords: Environment, Longitudinal Study, Perceived Air Quality Acceptability (PAQA), Thermal Acceptability (TA)

1 Introduction
An acceptable thermal and perceived air quality environment is one important goal of environmental design. Evidence in the literature indicates that thermal acceptability (TA) may affect occupant productivity or working efficiency (Wargocki and Seppänen, 2006), and perceived air quality acceptability (PAQA) was found to be associated with a number of sick building syndrome (SBS) symptoms (Cheong et al., 2006; Wargocki et al., 2000).

Prior TA and PAQA studies have usually been conducted in controlled environmental chambers or using cross-sectional field surveys focusing on specific environments, such as offices, residences and classrooms (Sun et al., 2012). Some studies have extended the measurement protocol to a longitudinal experiment, evaluating over longer periods the assessment of acceptability and monitoring a few environment parameters, such as air
temperature $T_o$ (°C), relative humidity $RH$ (%) and carbon dioxide mixing ratio $CO_2$ (ppm) at a fixed location (e.g., Pei et al., 2015). In studies with a large sample size with different participants, variability of the acceptability responses has usually been attributed to personal factors. Beyond the physiological attributes, a person’s assessment of environmental acceptability can also be psychologically affected by past experience, expectation, environmental context, the availability of environmental control, and the thermal and perceived air quality history of the subjects (Frontczak and Wargocki, 2011). Despite such indications about the importance to personal factors on TA and PAQA studies, existing survey methods have been limited in evaluating the influence of such differences.

To contribute acceptability assessments, we conducted a longitudinal experiment that combined assessments of thermal and perceived air quality acceptability with real-time personal continuous monitoring of $T_o$, $RH$ and $CO_2$. Potential influencing factors might include, but are not limited to, short-term changes in the objective physical parameters, differences in location and associated expectations, current ventilation status and occupant’s habits with regard to controllable parameters (such as window opening or air-conditioner operation). The advantages of longitudinal study that follows people include its ability to trace the history of individual exposure to physical parameters and the possibility to study the influence of personal expectations in various environments, which is a pioneering step to identify unknown confounding factors that driving occupant’s thermal and perceived air quality acceptability responses.

The objective of this paper is to identify the variation of TA and PAQA for the same group of participants in different locations with respect to physical parameters change ($T_o$, $RH$ and $CO_2$), air-conditioning status and occupant’s habits regarding thermal control in their sleeping environment using the personal continuous monitoring method. The study is conducted in a tropical setting in which two modes of thermal environmental control in the sleeping environment are common and distinct: open windows and closed windows with the operation of split-unit air conditioning. The thermal environment for sleeping reflects a high degree of autonomous choice, which can reflect people’s preferred status for ventilation and thermal environmental control.

2 Methods

Subject’s backgrounds

Fifteen educated young adult subjects living in Singapore participated in this study. The participants’ demographics and air-conditioner usage habits at home were collected, including age, gender, body height and weight, action priority when feeling hot (i.e. adjustment to clothing, window, cooling fan and air-conditioner), number of air-conditioner units at home and their sleeping ventilation status (i.e. sleeping in an air-conditioned bedroom (AC group) or in a bedroom with window open (AV group).) In an adventitiously ventilated (AV) environment, ventilation is incidental, and the ventilation system has not been taken into account and designed to achieve any particular code, standard or best practice (Schiavon, 2014).

Physical measurements

Each participant carried a portable sensor, which recording air temperature $T_o$ (°C), relative humidity $RH$ (%) and carbon dioxide mixing ratio $CO_2$ (ppm) at 1-minute intervals, continuously, for seven consecutive days. The subjects were instructed that the sensor should be carried or kept near the participant at all times during the measurement period. The real-
time continuous measurement revealed information about environmental conditions in relation to the participant’s activity patterns and their exposure to environment parameters. The chosen data logger was CM-0018 (CO2Meter Inc., Ormond Beach, FL, USA) with sensor accuracy of ±30 ppm ± 3% of the measured value for $CO_2$, ±0.4 °C for $T_a$ and ±3% for $RH$ (CO2Meter, 2014).

**Subjective acceptability survey**
An online survey was established to elicit and record each subject’s instantaneous evaluation of thermal acceptability (TA) and perceived air quality acceptability (PAQA) (SinBerBEST, 2015). For acceptability, the subject marked their response on a continuous scale from clearly acceptable (+1) to just acceptable (+0.1) and from just unacceptable (-0.1) to clearly unacceptable (-1). In this scale, subjects must distinguish clearly between acceptable and unacceptable. A response was expected after each environment change (i.e. home > outdoor > transit > office) throughout a day, yet was constrained by the participant’s availability.

**Activity schedule record**
Participants were also asked to record their daily activity schedule and the characteristics of each perceived environment during the measurement period, including the time of entry in each place, a description of the type of location (including home, workplace, outdoor, restaurant and vehicle, and places not in these categories were to be clearly defined in remarks), their activity (walking, sleeping, working, etc.), air-conditioning (AC) status (on / off) and window status (open / close). It is noted that the “AC group” classified under subject’s backgrounds only refers to participants who slept in an air-conditioned bedroom; it does not necessarily imply that the AC group participants always operate their air-conditioner at home.

**Data analysis**
A local polynomial regression fitting method, ‘loess’ function in R programming, was applied to visualize the non-linear association between the evaluated acceptabilities (TA and PAQA) and potential predictor variables. The regression line was fitted locally by weighted least-squares with an approximation of the 95% interval bounds in grey shading. Furthermore, the Wilcoxon rank sum non-parametric test, also known as the Mann-Whitney test, was used to identify any difference of two distributions by a location shift. If the computed $p$-value is less than 0.05, the null hypothesis of ‘observations come from the same population’ was rejected.

3 **Results and discussions**
Table 1 shows the results of overall measured parameters ($T_a$ (°C), $RH$ (%) and $CO_2$ (ppm)) and surveyed acceptability (TA and PAQA) classified in five different environments. Measurement samples at a location outside of the five categories are not considered due to limited data. The cumulative data count suggested that participants spent most of their time at home, followed by the workplace, outdoors, in restaurants and in vehicles.

Owing to its geographical location in a tropical region, the outdoor environment recorded in Singapore was usually hot (10 percentile, median, 90 percentile = 26.4, 29.7, 31.8 °C) and humid (59, 70, 81% RH). About two-thirds of the samples acquired at home were without air-conditioning and the physical parameters were comparable to those outdoor (28.2, 30.6, 31.7 °C; 62, 69, 75%). In the air-conditioned home environment, the temperature and humidity were, on average, 2.6 °C and 8.6% lower. The carbon dioxide mixing ratio at home with AC on was higher (557, 1003, 2227 ppm) than in the cases without air-conditioning (410, 574, 1260 ppm). Similarly, the restaurant environment included both AC (N = 3623) and non-AC (N = 2472) samples. Sampled $T_a$, $RH$ and $CO_2$ at AC restaurants were 23.1, 25.0, 29.9 °C; 52, 59,
70%; and 498, 713, 1432 ppm, while at the non-AC restaurants values were found on average to be 2.8 °C and 3.1% higher but 330 ppm lower. All measured samples in vehicle and workplace environments were with air-conditioning operating. Workplaces were equipped with centralized air conditioning with fresh air supply. The \( T_a \) was (24.1, 26.0, 27.7 °C) and the \( CO_2 \) mixing ratio was (409, 506, 868 ppm). In vehicles, the collected \( RH \) (43, 55, 71%) was found comparable with the workplace, but a higher \( T_a \) (26.0, 28.4, 30.9 °C) was recorded. Also, the \( CO_2 \) mixing ratio (447, 1327, 3053 ppm) in vehicles was found to be much higher than in all other environments, especially during rush hour with high occupant density in vehicle cabins such as buses and the rail mass rapid transit system (MRT). Table 1 also summarizes the surveyed subjects’ assessment of acceptability. The TA and PAQA were evaluated as acceptable at levels above 80% at all locations, except outdoors (TA: 50%, PAQA: 76%) and in vehicles (TA: 55%, PAQA: 36%).

### Table 1: Overview of measured and surveyed data in different environments

<table>
<thead>
<tr>
<th>Percentile</th>
<th>Home (N = 90963)</th>
<th>Outdoor (N = 6610)</th>
<th>Restaurant (N = 6103)</th>
<th>Vehicle (N = 4938)</th>
<th>Workplace (N = 38384)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( T_a ) ( RH ) ( CO_2 )</td>
<td>( T_a ) ( RH ) ( CO_2 )</td>
<td>( T_a ) ( RH ) ( CO_2 )</td>
<td>( T_a ) ( RH ) ( CO_2 )</td>
<td>( T_a ) ( RH ) ( CO_2 )</td>
</tr>
<tr>
<td>10%</td>
<td>26.2 56 428</td>
<td>26.4 59 406</td>
<td>24.4 53 407</td>
<td>26.0 43 447</td>
<td>24.1 47 409</td>
</tr>
<tr>
<td>25%</td>
<td>27.9 61 513</td>
<td>28.1 65 420</td>
<td>26.3 56 448</td>
<td>27.1 49 760</td>
<td>25.1 53 453</td>
</tr>
<tr>
<td>50%</td>
<td>29.7 65 717</td>
<td>29.7 70 466</td>
<td>27.5 60 590</td>
<td>28.4 55 1327</td>
<td>26.0 56 506</td>
</tr>
<tr>
<td>75%</td>
<td>30.9 70 1070</td>
<td>31.0 75 550</td>
<td>29.9 67 780</td>
<td>29.8 62 2152</td>
<td>26.8 60 602</td>
</tr>
<tr>
<td>90%</td>
<td>31.6 74 1520</td>
<td>31.8 81 740</td>
<td>31.4 71 1247</td>
<td>30.9 71 3053</td>
<td>27.7 90 868</td>
</tr>
</tbody>
</table>

N = Number of measured samples; sampling time resolution = 1 min.

Figure 1 presents a boxplot of TA and PAQA in the five different microenvironment categories. Higher thermal acceptability was found in restaurants, workplaces and at home, respectively, with median values of 0.40, 0.44 and 0.55. A lower median TA was observed in vehicles (0.11) and half of the outdoor TA votes were “unacceptable” with a median value of 0.12. For perceived air quality acceptability, high median PAQA value was observed at home (0.63), at the workplace (0.62), in restaurants (0.59) and outdoors (0.51), but a much lower median PAQA (0.29) was reported in vehicles. The high \( CO_2 \) mixing ratio in vehicle cabins (2152 ppm at the 75th percentile and 3053 ppm at the 90th percentile) could be one contributor to unacceptable air quality, but this interpretation may not equivalently hold when applied to other places. No unacceptable PAQA was recorded at home when the AC was on. The criteria of people’s assessment of acceptability might vary with location and with the subject’s expectation, and changes in the physical parameters (i.e. \( T_a \), \( RH \), \( CO_2 \)) may not be the only contributing factors.

Figure 2 illustrates the relationships between surveyed subject’s acceptability assessments (TA, PAQA) and measured environmental parameters (Ta, RH, CO2). Clearly, for the tested conditions, there is no relationship between acceptability (both TA and PAQA) and Ta and RH ( ). The weighted-regression lines suggest generally acceptable conditions within the sampled temperature and relative humidity ranges (22.5–32.5 °C and 40–80%). The highest TA (0.41) was observed when Ta was 26.5 °C. These diagrams show that participant’s thermal or perceived air quality acceptability cannot be determined simply by using Ta and RH.
Figure 1 Overview of subject’s assessments of thermal acceptability (TA) and perceived air quality acceptability (PAQA) in various places.

Figure 2 Overall relationships between assessed acceptabilities (TA/PAQA) and environmental parameters ($T_a$, $RH$, $CO_2$)

Figure 2 also shows an almost negative linear relationships are seen between acceptabilities and the $CO_2$ mixing ratio. The regression lines cross the “just unacceptable” region at a $CO_2$ mixing ratio of approximately 1500 ppm. The negative association between PAQA and $CO_2$ mixing ratio is reasonably attributed to insufficient ventilation, but the same trend in TA samples remains physically unexplained. Another analysis, not reported here, shows a generally positive relationship between TA and PAQA, which could be a confounding reason for the similar trend between assessed acceptabilities and $CO_2$ mixing ratio. This evidence suggests that apart from physical parameters some other factors might have to be considered for fully predicting thermal acceptability.

Figure 3 illustrates the relationships (a) between TA and $T_a$ and $RH$ and (b) between PAQA and $CO_2$ mixing ratio, when data are clustered by location. (The outdoor environment is excluded
owing to insufficient data.) Thermal acceptability was found to decrease with higher air temperature and relative humidity at home and in restaurant environments. Less than 10% occurrence of thermal unacceptable was reported in air-conditioned homes and restaurants, but the proportion dissatisfied with the thermal environment increased to 41% and 57%, respectively, in non-air-conditioned homes and restaurants. On the other hand, all sampled workplaces and vehicle cabins were air-conditioned. Although a weak association was observed between thermal acceptability and environmental parameters, the data suggest that lowering the temperature in these air-conditioned places did not necessarily enhance the perceived thermal acceptability. Dissatisfaction regarding over-cooled working environments have been reported for Singapore offices (Sekhar, 2016). The percentage of thermal acceptance was found to be less than 80% when \( T_a \) was lower than 25 °C, according to a bin temperature of ±0.5 °C, in the workplace. It dropped below 50% in vehicles when \( T_a \) was below 25 °C or above 32 °C. No remarkable trend was found between TA and \( CO_2 \) mixing ratio in any of the environment.

For PAQA, the no unambiguous associations with \( T_a \) and RH were found, but a relationship to \( CO_2 \) mixing ratio was observed, especially at home and vehicle environments. Interestingly, an increase in the PAQA value with higher \( CO_2 \) mixing ratio was reported, which likely happened in homes with air-conditioning on and the window closed. In addition, a closed window could reduce the penetration of outdoor pollutants, thus producing a higher acceptability to household air quality, especially during the haze period in Singapore (Zhou et al., 2015). The worst PAQA was found inside vehicle cabins, where more dissatisfied air quality votes were found at \( CO_2 \) mixing ratios above 1000 ppm. Unacceptable air quality could be due to low outdoor air flow rate per person and close proximity among occupants (Moreno et al., 2015). The workplace was found to have the highest PAQA among all environments (i.e. 90% of the votes were acceptable). The few dissatisfaction votes could be attributed by many possible reasons, but no evidence emerged to show a clear relationship between PAQA and the measured parameters at the workplace. Comparing Figures 2 and 3, location was considered as an important factor in identifying the associations between the perceived acceptabilities of indoor environments and corresponding objective physical parameters.

Figure 4 shows boxplots for the TA and PAQA performance in relation to the air-conditioning on/off status at home and in restaurant (left). It also presents (right) acceptability results for home and workplace with subjects sorted according to whether they slept with air conditioning on (AC) or with windows open (AV). The data suggest that not operating an air conditioner may reduce thermal acceptability in restaurants \( (p < 0.05, \text{Wilcoxon rank sum test}) \). An analogous result is seen in homes with improved acceptability measures with air conditioning operated (TA and PAQA: \( p < 0.05 \)), which limits exposure to warm and humid outdoor air together with limiting the penetration and persistence of outdoor pollutants. These results are consistent with the previous discussion of Figure 3. The data in Figure 4 also suggest that there is no significant difference between air-conditioning ventilated (AC) or adventitiously ventilated (AV) groups for TA and PAQA outcomes at home \( (p > 0.4) \). However, somewhat surprisingly, subjects who slept with air conditioning judged that their workplace had significantly lower acceptabilities (TA and PAQA, \( p < 0.05 \)). It may be that the AC group was accustomed to control their sleeping environment, and may have been more unsatisfied than the AV group with the uncontrollable ventilation and thermal environment in their workplaces.
Figure 3 Relationship between thermal acceptability (TA) to measured environment parameters ($T_a$, RH, $CO_2$) in different environments
4 Conclusion

Personal longitudinal monitoring experiments were conducted to investigate participants’ assessment of thermal acceptability (TA) and perceived air quality acceptability (PAQA) in different locations with respect to objective physical parameters ($T_a$, RH and CO$_2$), air-conditioning status and occupant’s sleeping ventilation habit. The findings suggest that clustering locations is important to better understand the associations between the environmental acceptabilities (TA and PAQA) and the measured physical parameters ($T_a$, RH and CO$_2$). The acceptability ratios of both TA and PAQA were greater than 80% in locations where people spent most of their time (home, workplace, and restaurants), but not outdoors and not in transportation vehicles. The worst PAQA, with acceptability ratio of 36%, was report in vehicle cabin, where an association of decreasing PAQA at higher CO$_2$ mixing ratio (median value = 1327 ppm) was observed. Greater acceptabilities were found when an air-conditioner was operated at home and in restaurant environments. In addition, both the air-conditioning ventilated (AC) and adventitiously ventilated (AV) sleeping groups were also satisfied with controllable ventilation at home, whereas the AC group assessed the thermal acceptability to be lower in the workplace than did the AV group. The database developed in this longitudinal experiment was capable to identify the thermal and perceived air quality acceptability trend under different environments. The next step of study would be focused on individual environment exposure analysis to assist future works on personal acceptability prediction.

References


SinBerBEST, 2015. Thermal Acceptability (TA) and Perceived Air Quality Acceptability (PAQA) online survey.


