Use of portable air purifiers in homes: operating behaviour, effect on indoor $PM_{2.5}$ and perceived indoor air quality

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Abstract

In much of the world, people spend on average 65% of their time indoors at home. It is, therefore, important to understand the quality of air in homes, and how best to improve it. Negative health impacts associated with exposure to particulate matter are well documented, and account for significant morbidity and mortality worldwide. Technologies are rapidly being developed and adopted to mitigate indoor air pollution, and portable home air purifiers (HAPs) are one of the most effective technologies available to clean the surrounding air of harmful pollutants of both indoor and outdoor origin. The aims of the research presented here were to explore the impact of a commercially available air purifier used in actual bedrooms on indoor

$PM_{2.5}$ concentrations and perceived indoor air quality, as well as to understand and describe how portable air purifiers are used by occupants. Results from the present study showed that $PM_{2.5}$ concentrations in bedrooms were reduced by a mean of 45% over 90 minutes with HAP use. Participants' subjective assessment of the indoor air when the HAP was on was positive. However, the predominant motivation and indicator of HAP use was thermal comfort, and not perceived air quality. If used properly, portable air purifiers used at home could be effective at reducing exposure to $PM_{2.5}$ indoors.

1 Introduction

Home, for most people, represents a place of comfort, safety and wellbeing, and, on average, people spend more than 65% of their time there [1]. It is important, therefore, to understand the quality of the air in homes, and how best to respond if it is poor. In many locations, air pollution concentrations, including particulate matter, can exceed standards imposed by the European Union and health-based guidelines developed by the World Health Organization for both chronic and acute exposure [2], and previous studies have recognized the contribution of indoor air pollution to total exposure [3, 4]. Negative health impacts associated with exposure to particulate matter, particularly that which is 2.5μm of less in aerodynamic diameter ($PM_{2.5}$), include: cardiovascular diseases [5], asthma [6], bronchitis [7], premature mortality [8-10] and lung cancer [11]. Numerous studies exist that consider the health benefits of different methods of particulate filtration [12-14], and technologies are rapidly being adopted to mitigate indoor air pollution. Portable air purifiers are one of the most effective technologies available to clean the surrounding air of harmful pollutants of both indoor and outdoor origin. The most common equipment currently available for in-home use are home air purifiers (HAPs) which utilize HEPA filtration as the primary mechanism of air cleaning. These devices have several advantages over other filtration methods, including they are simple to install, can be located where people spend most of their time, can be relocated, and they do not require a central air handling system. Previous research has reported substantial and significant reductions in $PM_{2.5}$ in spaces using these devices [15, 16]. However, much of this research has targeted occupants with specific health conditions (e.g. asthma), or specific outdoor events (e.g. wildfires) [17-22].

In terms of links between measured and perceived indoor air quality, the evidence is limited. Langer et al. [23] assessed the perception of air quality in homes in France and found that there was little correlation between occupants' perceived air quality and the measured parameters (including particulate matter). In the study, visitors to the homes did a better job of assessing air quality, but their perceptions were strongly correlated with the smoking habits of the occupants and the season in which they visited. The pollutants with the largest impact on the perception of indoor air quality were volatile organic compounds including, acrolein and acetaldehyde. People's perception of air quality has also been shown to be more strongly influenced by thermal conditions and relative humidity [24]. There is little evidence that people readily perceive poor air quality due to $PM_{2.5}$. A study by Rotko et al. [25] found that, although people expressed annoyance with air pollution, there was little correlation between annoyance and measured $PM_{2.5}$ concentrations. Because people may not perceive $PM_{2.5}$ and therefore may not act to mitigate unhealthy levels at homes, where ventilation may be inadequate, there is a substantial exposure risk.

Building ventilation systems, infiltration rates, and location of the air purifier in the building or flat are all well considered and described in the literature as factors that affect air purifier performance [26-28]. However, how people use air purifier devices has not been adequately studied. Whilst other occupant behaviours affecting indoor air quality such as window opening behaviour [29], and air-conditioning use relative to thermal comfort [30], have been well documented, only a couple of studies have looked directly at HAP use and its drivers. One such study by Pei et al. [31] found that in 43 residences in China, that were provided with portable air purifiers, 81.4% did not use the device at all, and of those that used it intermittently (18.6%), the average operating time was between 1-4 hours per day. They concluded that these patterns of use would be insufficient to adequately reduce indoor $PM_{2.5}$ levels. Very different use patterns were reported, although not monitored, in a study from the California Air Resources Board [32]. They found that 57% of owners of air purifiers claimed to use them continuously every day. There is little to explain the significant difference between these two studies, other than speculation that the motivation of the frequent air purifier use reported in California was due to perceived health benefits of their use.

The aims of the research presented here were to explore the impact of a commercially available air purifier used in bedrooms on indoor $PM_{2.5}$ concentration, and perceived indoor air quality, as well as to understand how portable air purifiers are used by occupants, their motivations, decisions, and actions over time.

2 Methods

2.1 Context

Conventionally, ventilation in U.K. residences has been through operable openings (i.e. windows and doors) as well as infiltration, and uncontrolled ventilation has been common. Building standards have changed to meet requirements for energy efficiency and carbon reduction which has lowered infiltration rates, making intentional ventilation paramount to keeping indoor air quality good [33]. Although there are several ways to achieve the required air exchange rates (in the U.K. for dwellings the rates range from 13 l/s for 1 bedroom to 29 l/s for 5 bedrooms), including continuous mechanical extract, or supply and extract with heat recovery, background ventilators remain a common approach. Background ventilators (e.g. trickle-ventilators), as with uncontrolled ventilation, do not provide any filtration capacity, leaving the indoor air quality heavily dependent upon the quality of the outdoor air. Additionally, for events of high indoor pollutant generation (e.g. cooking), ventilation rates may be inadequate.

The work presented here was generated from a larger study that included the monitoring of indoor air quality, personal exposure monitoring, and the assessment of occupant behaviour in relation to portable air purifiers across multiple cities. The study utilised a convenience sample of 20 households which, after dropouts, resulted in a sample of 18 flats in London. Participant volunteers were asked to complete an intake and exit interview, as well as several shorter surveys throughout the study period. Flats were monitored for six months, from July until the end of December, to monitor conditions across three seasons. This timeframe allowed for observations into occupant behaviour related to window operations, air purifiers, and heating systems.

The 18 residences were located within three buildings at two sites (Site A and B) in east London. The buildings were constructed within the last decade, and relied upon natural ventilation and trickle-ventilators in the non-heating months. Eleven flats at one site (Site A) had mechanical ventilation with heat recovery (MVHR) that was available during the heating season with a by-pass mode for use in non-heating times. The units were decentralised, one unit per flat, with fan efficiencies between 75-77%, and heat exchanger performance compliance of 92 t0 93 per cent. Filtration with the MVHR was minimal (ISO Coarse 45%), and filter changing and maintenance was intermittent, at best. None of the flats had any air conditioning systems. Previous work at Site A included a pressure test which found an air permeability of 2-3 $m^3/(h.m^2)$ at 50Pa. Given the age and building characteristics of the other building, the infiltration rate is estimated to also be less than 5 $m^3/(h.m^2)$ at 50Pa. Bedrooms in which the HAPs were located, ranged in size from approximately 10.5m^2 to 12.5m^2 with a ceiling height of 2.5m, and typically had one operable window approximately 1.6m^2. Demographic information for all participants can be found in Figure 2-1 below. The households were provided with home air purifiers (HAP) for use in the main bedroom. The HAPs used in this study had a pre-filter, an activated carbon filter, and a HEPA filter with a clean air delivery rate (CADR) of 500 m^3/hour with a 0.3µm particle removal efficiency of 99.97%, for room sizes up to 60 m^2. Each HAP had a built-in sensor for measuring $PM_{2.5}$ and sent information via the cloud to the manufacturer of ON/OFF status, operation mode (e.g. fan speed), and $PM_{2.5}$ levels. To avoid sleep disturbance due to noise from the sensors, separate $PM_{2.5}$ sensors were installed in all dwellings in a room adjacent to where the HAP was situated, typically the living room. Outdoor $PM_{2.5}$ levels were monitored at the ground level of each site. Surveys were conducted at the households to gather information about occupancy, physical characteristics of the dwelling (e.g. area, carpeted, etc.), and occupancy patterns and behaviours. Survey structure and content were adapted from those developed for the housing section of the SINPHONIE project [34], as well as a section of the Building Users' Survey Methodology (BUS) [35].

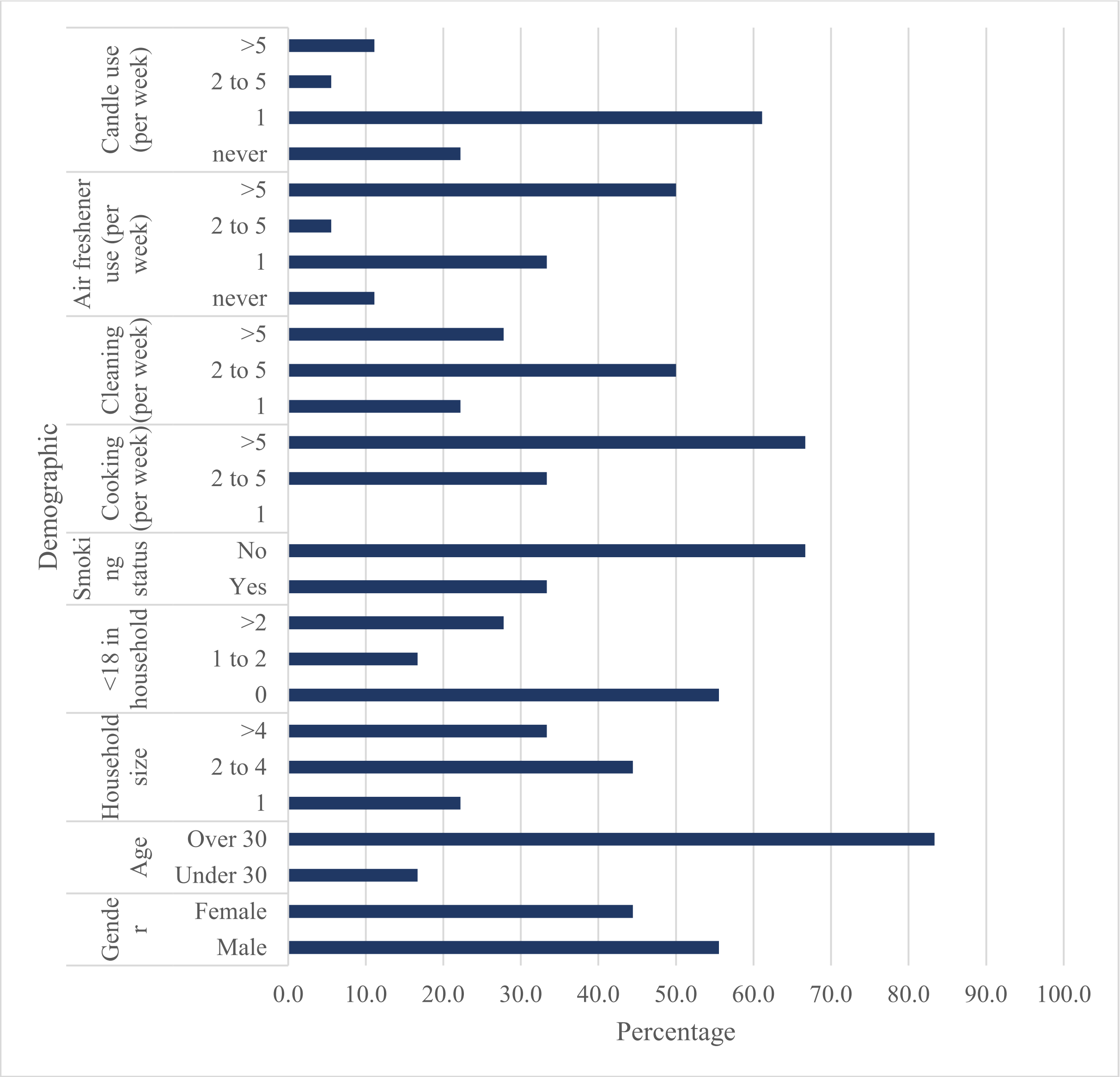


Figure 2-1 Demographics of participating households.

Indoor and outdoor air quality sensors in London were Eltek TU1082 – AQ110/112. A summary of parameters for these transmitters can be found in Table 2-1 below.

2.2 Air quality measurement

Eleven flats from Site A and seven flats from Site B were monitored from early July 2019 until the end of December 2019. Overall, 18 living rooms, 17 bedrooms, and 60 opening areas (18 balcony doors and 42 windows) were monitored by sensors which worked in a clustered sensor network. After testing the onsite transmission signal strength, all 18 flats were allocated to 11

Eltek Squirrel SRV250 data loggers. This architecture enabled real-time data collection from each flat to be sent and stored to an online server every 5 mins using available 3G networks. Due to the availability of a constantly updated database, a core part of data quality assurance work was automated to check for power-off, signal loss, or other issues. Problems were quickly identified, and the appropriate action was taken to minimise data loss to the greatest extent. The Eltek indoor air quality transmitters, AQ110/112, were placed at a height of 1.5 - 1.7m above the finished floor in the living room of each flat to avoid disruptions in occupants' use of their homes. Eltek GD47B sensors were located at the same height in the bedroom where the HAP was used to measure air temperature, relative humidity and CO_2. An AQ110/112 sensor was deployed outside of each building to measure the real-time outdoor environmental pollutant level. Crilley et al. [36] previously described the use of these optical particle sensors for ambient air quality monitoring and found that when properly calibrated and adjusted for relative humidity they are adequate for the assessment of airborne particle mass concentrations. The buildings were all located in relatively dense urban mixed-use areas adjacent to high traffic roads.

Table 2-1 A summary of monitored parameters and resolution of the Eltek AQ110 sensors.

Parameter	Sensor	Range	Resolution	Accuracy
Temperature	Thermistor	-30.0 to 65.0°C	0.1°C	±0.2°C at 20°C ±0.4°C for -5 to 40°C ±1.0°C for -20 to 65°C
Relative Humidity	Capacative	0.0 to 100.0%	0.10%	±2% RH (0 to 90% RH) ±4% RH (0 to 100% RH)
CO_2	Non-dispersive infra red (E+E Electronik)	0-5000ppm	1ppm	<±50ppm, +3%
Particulate Matter PM_1 ($\leq 1 \mu m$)	Optical Particle Counter (Alphasense OPC-N2)	0.00 to 500.00 $\mu g/m^3$	0.01 µg/m3	
Particulate Matter $PM_{2.5}$ ($\leq 2.5 \mu m$)	Optical Particle Counter (Alphasense OPC-N2)	0.00 to 500.00 $\mu g/m^3$	0.01 µg/m3	
Particulate Matter PM_{10} ($\leq 10.0 \mu m$)	Optical Particle Counter (Alphasense OPC-N2)	0.00 to 500.00 $\mu g/m^3$	0.01 µg/m3	
Airflow	-	0.00 to 500 ml/s	0.01 ml/s	
NO_2	Electrochemical (Alphasense NO2-A43F)	0.00 to 3.00 ppm	0.1 ppb	
CO	Electrochemical (Alphasense CO-A4)	0.00 to 300.00 ppm	0.01ppm	
TVOC	Photoionization detctor (Alphasene PID-AH2)	0.00 to 50.00 ppm	10ppb	

2.3 Window operations

Window state (open/closed) was monitored in each flat to assess the impact on air purifier performance. The window sensor Eltek GS34, used magnetic reed switches to monitor the status of openings including balcony doors and windows in both living rooms and bedrooms.

2.4 Crossover study design

The cross-over structure of the study was applied to answer research questions regarding the performance of the home air purifier with respect to $PM_{2.5}$ indoors, and in relation to the outdoor concentration of this pollutant. The home air purifier (HAP ON) was compared with respect to using no purification device (HAP OFF) as well as using the HAP always ON at a low fan speed (HAP SLEEP). Pollutant levels were measured every 5 minutes, and the use of the purification device was evaluated through interviews pre-installation (baseline) and at the collection of the HAPs. The World Health Organisation (WHO) Air Quality Guidelines (2008), which are health-evidence based and more stringent than the imposed EU standards, were used as a reference for both outdoor and indoor air in this study. This recommendation is for a short-term exposure limit of 25µg m^{-3} 24-hour mean, and long-term limit of 10 µg m^{-3} annual mean.

The cohort of London participants was divided into four (4) roughly equal tracks, three with alternating configurations of HAP use outlined above, and one with the HAP to use as they wished for the duration of the study. Each phase of the crossover period lasted a minimum of three weeks. For one week of each phase, participants were sent short surveys each day that asked them about the quality of their sleep and wellbeing during the previous day.

2.4.1 Crossover Tracks

Crossover tracks with the number of participants, the dates of the crossovers, and the state of the air purifier use are listed in Table 2-2.

Table 2-2 Crossover tracks, each period lasted a minimum of three weeks.

No. of apartments	First period (13/08/19-03/09/19)	Second period (03/09/19-24/09/19)	Third period (24/09/19-15/10/19)
4	HAP ON	HAP ON	HAP ON
4	HAP ON	HAP OFF	HAP SLEEP
5	HAP SLEEP	HAP ON	HAP OFF
5	HAP OFF	HAP SLEEP	HAP ON

2.4.2 HAP Settings

HAP ON

The air purifier was switched on and participants could change the settings (e.g. turn-off, change fan speed, etc). The air purifier was installed in their home and they could use it according to their own preferences. They could do the following in these 3 weeks:

- Turn the air purifier on
- Turn the air purifier off
- Select the airflow setting: Settings are “sleep” setting SL (lowest airflow), fan speed 1 (low), fan speed 2 (medium), fan speed 3 (high), turbo setting (maximum airflow), or automatic airflow.

HAP OFF

The air purifier was switched off.

HAP SLEEP

The air purifier was switched on to “sleep” mode for all three weeks. This is the lowest ventilator speed. The status of the HAP (i.e. ON, OFF, Fan Speed) was monitored via a cloud connection with the manufacturer. Compliance with crossover protocol was evaluated based on the actual operation of the HAP via data from the device itself. During data analysis participants were classified, and data were analysed, based upon the actual air purifier use.

2.5 Semi-structured interviews

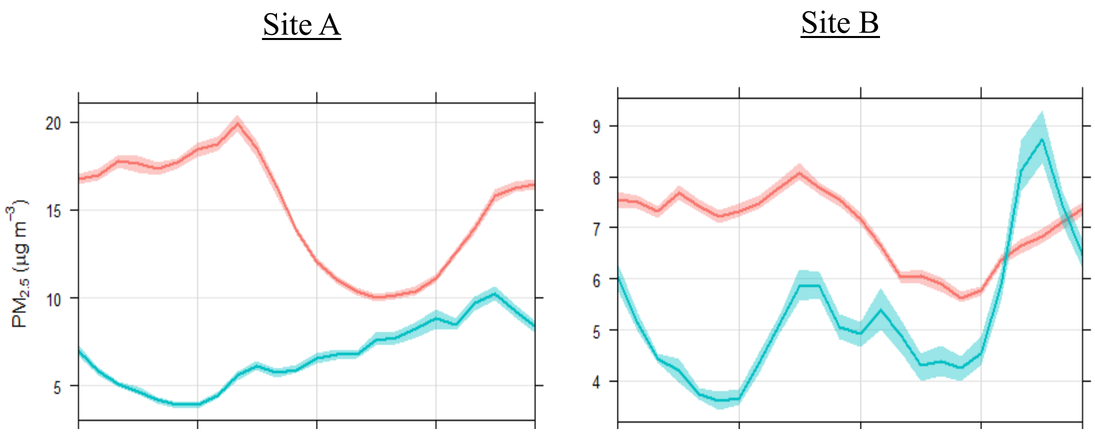
At the first site visit, semi-structured interviews were conducted to establish a baseline of the occupants’ overall satisfaction with the dwelling, their general health and wellbeing, and sleep quality. A section of the Building Users’ Survey Methodology (BUS) [35] was used to determine the occupants’ opinions on various aspects of the indoor environment of their home [37]. Mental and physical health were self-reported using the Short Form health survey (SF-12) [38]. Participants were asked about their sleep quality using the Pittsburgh Sleep Quality Index (PSQI) [39]. These components are pooled to create a global score for the prior 1-month interval. Participants were also introduced to the use of the air purifier, and the other monitoring equipment was installed. Upon completion of the 9-week crossover study, another semi-structured interview was performed in an effort to determine any effects on participants’ sleep and wellbeing, as well as to understand how the air purifiers were utilised by occupants. After the cross-over study period, all 18 households agreed to continue with monitoring to the end of the calendar year. This extension allowed the capturing of data during the heating season.

3 Results

3.1 Indoor air quality

This work focussed on the indoor air quality in homes that use air purifiers. Homes monitored during the study period had good air quality when measured against WHO limits. Indeed, there were few times or days during the study period where outdoor air exceeded the limits. Evaluating against short term limits: no single midnight to midnight day exceeded 24-hour WHO limits, a running 24-hour mean of PM$_{2.5}$ exceeded WH0 24-hour limits on 2 occasions in indoor levels, accounting for less than 0.1% of total monitored hours. In outdoor levels, the WHO limit was exceeded on two occasions at each site, but this was still less than 1% of the total hours. It is worth noting however, no safe exposure limits have been established for PM$_{2.5}$, and as almost two-thirds of our time is spent at home, even small reductions in concentrations are expected to be impactful. Pope et al. [11] reported that each 10μg/m^3 elevation of PM corresponded to a 4-8% increased risk of mortality.

The typical daily patterns of PM$_{2.5}$ in living rooms and outdoor concentrations illustrate the daily dynamics between indoor and outdoor sources, as well as when the internal generation of pollutants may occur (Figure 3-1). This figure shows average hourly values across a day,


Site A

Site B

Figure 3-1 Aggregated (typical daily patterns) of outdoor and indoor PM2.5 in living rooms - site A left, site B right aggregated for all days and all apartments for the two London developments. Particulate matter levels outside at both sites peak around 8 am, most likely associated with peak morning road traffic, before dropping in the afternoon, with a slight rise during evening rush hour. Indoor levels at site B shows a morning peak correlating with outdoor levels, and a large evening peaks attributable to cooking activities. Site A concentrations are relatively flat throughout the day with a small evening increase.

The air quality in the living rooms of London homes using air purifiers in the bedroom exhibited a reduction in mean concentration with a small drop in peaks. Although modest, this reduction was statistically significant (*p<0.001*) based upon the non-parametric Kruskal-Wallis test. A non-parametric test was used due to the skewed distribution of pollutants. Figure 3-2 below illustrates the differences in $PM_{2.5}$ concentrations in living rooms with the air purifiers ON or OFF. The air purifiers were not designed or intended to purifier the air beyond the room in which they were installed, but this does indicate the general efficacy of the devices and the sensitivity of the sensors in the living rooms to record even small changes in concentrations of $PM_{2.5}$. The median concentration in living rooms with the air purifier OFF in the bedroom was 3.5 µg/m^3. The median concentration in living rooms with the air purifier ON in the bedroom was 3.1 µg/m^3.

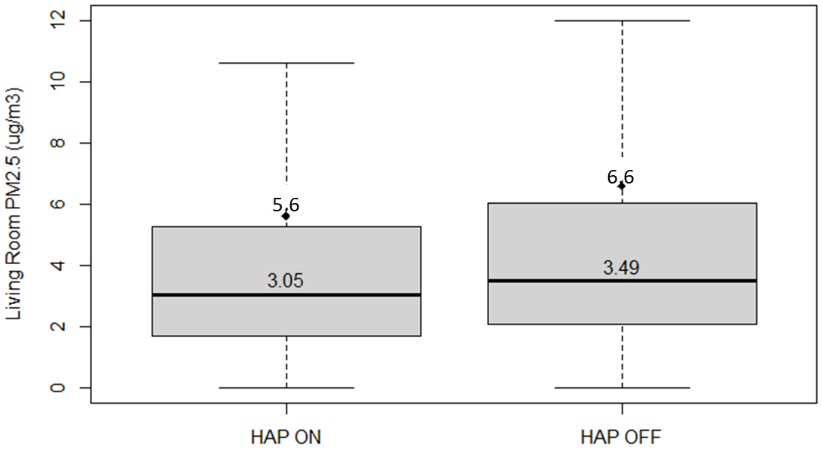


Figure 3-1 $PM_{2.5}$ concentration in living rooms of participants with air purifiers ON (any fan speed or SLEEP mode) or OFF with medians indicated by dark horizontal lines, means as points.

When measurements from the HAPs' sensors from all participant bedrooms are combined, a clear decay curve can be seen from the onset of HAP use to 100 minutes run time (Figure 3-3). When running with the windows closed, a median percentage reduction of 20% can be observed from initial concentrations after 30min. Reduction in $PM_{2.5}$ concentration was observed in cases of bedroom windows opened as well as closed, despite the recommendation from the manufacturer that the HAP be operated with the window closed for optimum performance. Window operations were important to understand due to potential drivers for HAP operation, air exchange rates, as well as the indoor concentrations relative to outdoor sources of $PM_{2.5}$. Figure 3-3 represents the aggregated performance of the HAP, it is important to note that not all run cycles resulted in the same reduction pattern, particularly in the presence of continued internal sources, re-suspension etc. From all run cycles, 56% of cases experienced a reduction on initial concentrations after 30 min. Similarly, a reduction of 50% on initial concentrations was observed after 60min of HAP operation in 45% of run cycles.

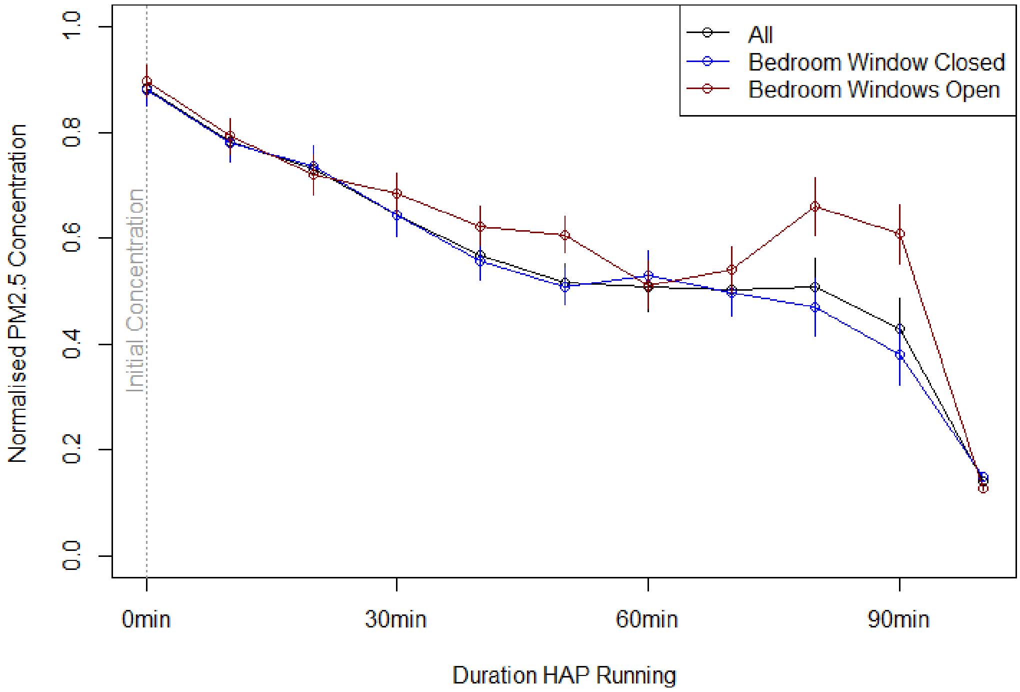


Figure 3-2 Change in the mean concentration of $PM_{2.5}$ in London bedrooms using home air purifiers. HAP switched ON at time 0, with minutes of run time shown. Vertical bars represent the standard deviation of the mean across all flat flats.

Normalised concentrations were used in the bedrooms because the sensors internal to the devices could not be fully calibrated. However, calibrated sensors collocated with the HAPs were in strong agreement with the levels measured by the air purifiers ($R^2 = 0.9$, RMSE = 4.5 $\mu g/m^3$, MBE = -0.16 $\mu g/m^3$). The normalised $PM_{2.5}$ concentration in the bedrooms of all flats is shown in the figure below (Figure 3-4). Technical specifications that include CADR (Clean Air Delivery Rate) by fan speed were not available for the HAPs used. Hourly patterns, however, indicate that the concentration of particulate matter is correlated with fan speed. That is, the higher the fan speeds the lower the concentration of $PM_{2.5}$.

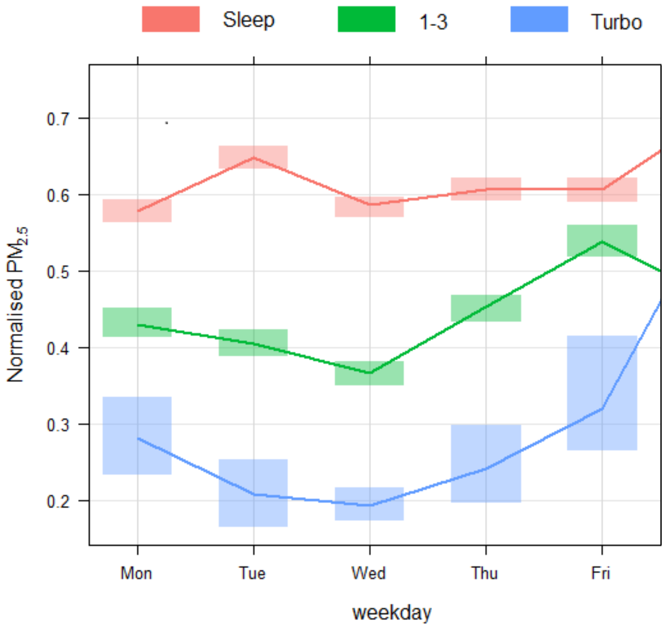


Figure 3-3 Changes in the concentration of $PM_{2.5}$ (normalised by the mean) in the bedrooms during typical work week under different HAP operational modes. Sleep = air purifier was on at the lowest fan speed. 1-3 = air purifier was being used, at any fan speed other than the highest, and turbo = the highest

3.3 Perceived indoor air quality

Sections of the Building Users' Survey [35] was used to assess the satisfaction of occupants on a number of indoor environmental factors. Of the 22 factors that were scored, only 3 were considered fully satisfactory: control overheating, control over lighting, and the stability of the temperature in winter. 11 factors were marginal including: overall condition of indoor air in summer and winter, control over ventilation, the odour of air in the summer, and comfort overall. Notably, 8 factors were unsatisfactory including: the humidity, stuffiness and stillness of the air in summer, the control overcooling, and the overall temperature in summer and winter. A summary of parameters that were found to be somewhat (amber) or completely (red) unsatisfactory are shown in is shown in Figure 3-5 below.

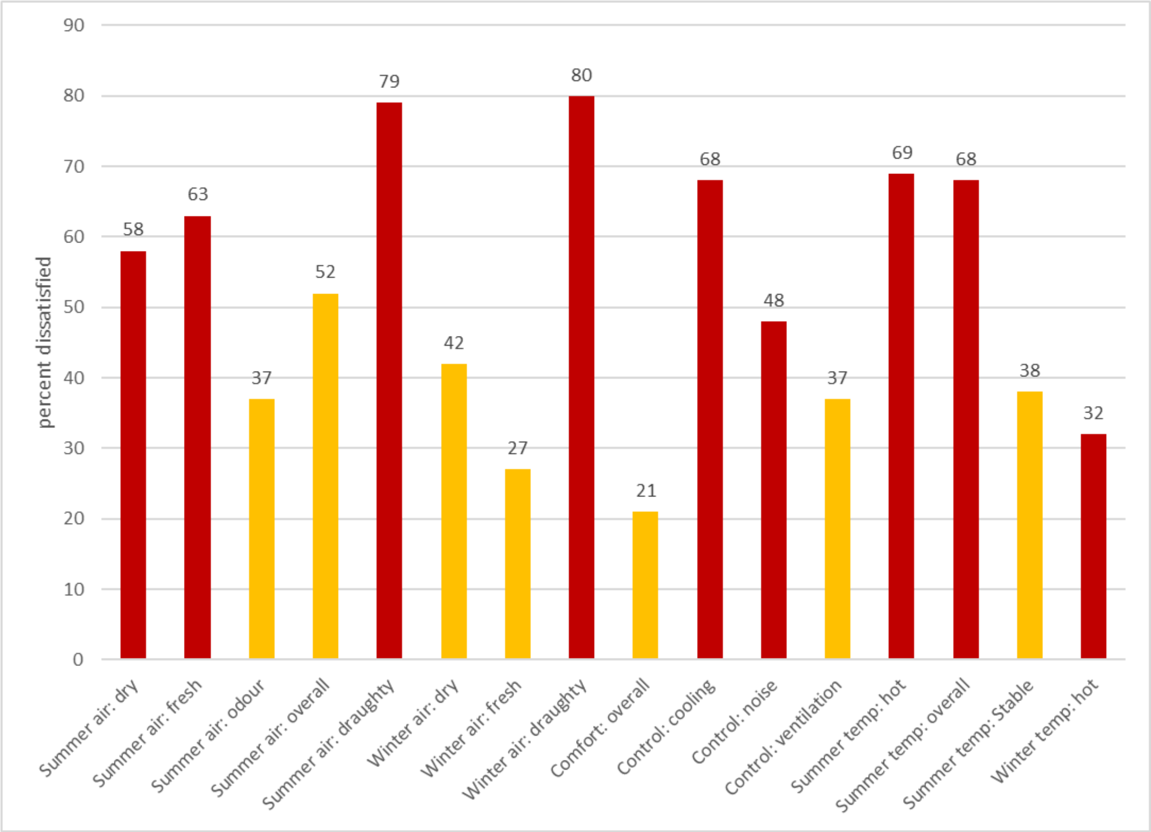


Figure 3-5 A summary of some of the parameters and percentage dissatisfied from the Building Users' Survey (BUS). Red bars are those parameters rated as wholly unsatisfactory.

Generally, occupants rated the indoor air quality poorer in the summer with a very high rate of dissatisfaction with the temperature, stuffiness and stillness of the air, as well as the control over cooling. Mean carbon dioxide levels measured in the flats were very often high, especially during the heating season in bedrooms (Figure 3-5). However the highest rates of dissatisfaction with the air did not correspond with the highest levels of CO_2, but rather with higher temperatures in the summer, indicating it is not air quality that is driving occupants’ satisfaction.

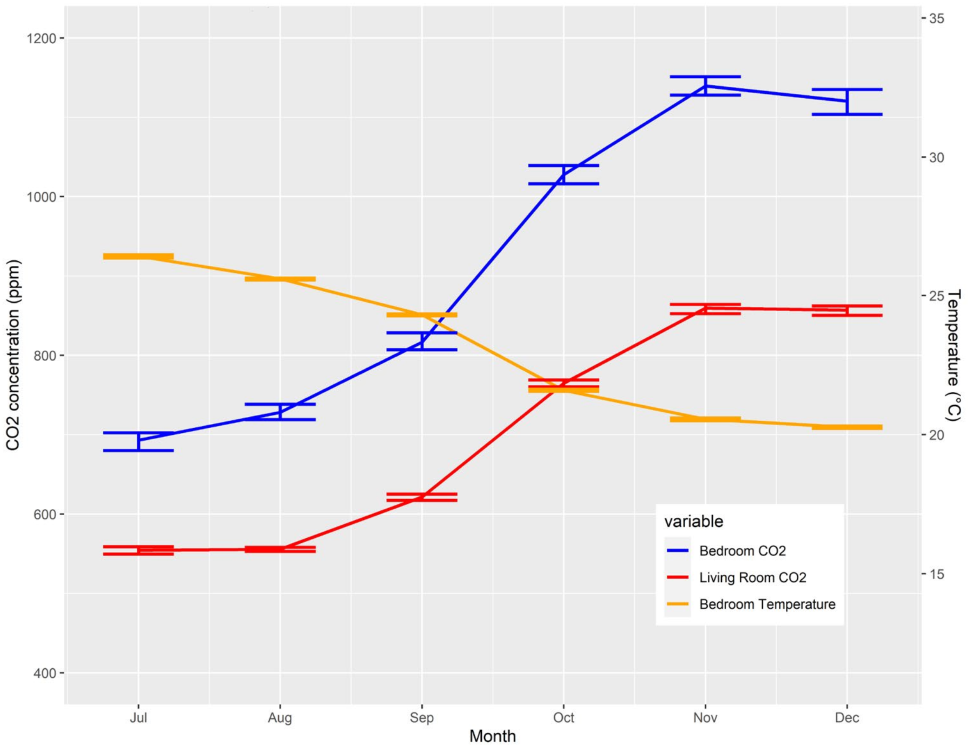


Figure 3-4 Mean temperature and CO_2 concentrations in living rooms and bedrooms throughout the study period

3.4 HAP operation behaviour

The pattern of use over time shows a pattern that could be due to the normal seasonal drop in temperature (Figure 3-6). However, it could have also been attributable to study “fatigue” or from a loss of interest in the device. There is a peak in use as the start of the study, perhaps related to a “new gadget” being introduced into the home, and then use slowly declines (with peaks that may correspond to directives of the crossover periods or periods of warm weather) into the cooler autumn and winter months. From interviews, people generally expressed more satisfaction with the overall air quality and comfort in the cooler months which could contribute to a decline in the perceived utility of an air purifier. Additionally, many residents reported that they believed the HAP cooled the room in which it was operating, and this may have been undesirable as temperatures dropped. During the crossover period of the study, when participants were instructed to use the HAP in any manner of their choosing, they used the HAP a mean of 19.2 hours per day, however most of that time (14.2 hours) the devices were set to the lowest fan setting (SLEEP) which may have been considered as a ‘standby’ mode mode and as previously demonstrated, has a lower impact on particulate concentrations (Figure 3-4). Use dropped to a mean of 3.7 hours on a fan setting higher than the lowest setting during the crossover period. Additionally, people interacted with the devices less often after the crossover period was complete, modifying the settings a mean of 5.1 times a day during the crossover, but only 3.0 times after.

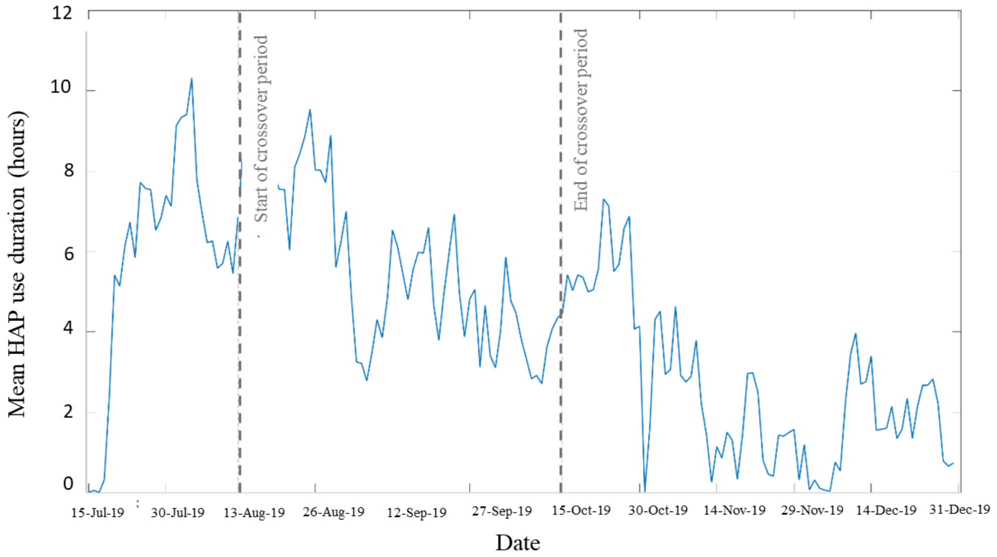


Figure 3-5 Change in HAP utilisation (hours per day) over the course of the study period excluding SLEEP mode. The crossover portion of the study is bracketed by the vertical dashed lines.

Given that residents expressed dissatisfaction with the temperature in their homes in summer and commented in interviews that they appreciated the “cooling” effect of the HAPs, the pattern of use displayed is not unexpected. There is a clear correlation between increasing temperatures and increasing HAP use as shown in the logistic regression model below (Figure 3-7). Similar models have been used to describe occupant behaviour related to window operations [40]. In this model, outdoor temperature was used as an explanatory variable to simulate whether the HAP was ON or not. The coefficients for this model are represented by the following expression, and are significant to the level of 0.05:

$$\text{Logit (probability of HAP ON)} = \log(p/(1-p)) = -2.83 + 0.082 * \text{Outdoor Temperature}$$

In the figure, the red X’s are the predicted probability of the HAP status (ON or OFF) based on outdoor temperature, and the green circles are 95% confidence intervals. It is clear that the trend of HAP operating was noticeably greater with increasing outdoor temperatures for example, the predicted probability that the HAP is ON is approcimately 0.53 when it is as hot as 35 °C outside. The model provides good statistical evidence for the anecdotal finding that participants’ HAP use is driven by the perceived cooling effects of the devices.

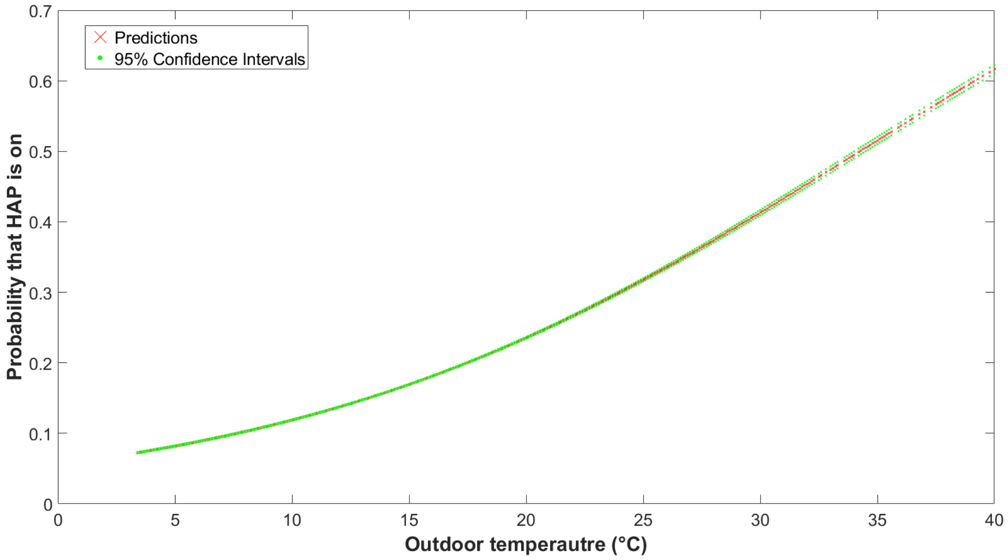


Figure 3-6 Probability of air purifier use in in relation to outdoor temperature ($p<0.001$)

Another possible motivation for HAP use could have been occupant health and wellbeing. Healthy adults were recruited, but having specific health conditions did not exclude people from participating. Fifteen of the participants reported having allergies and/or itchy and watery eyes, 4 people reported having asthma, 3 reported frequent respiratory infections, and 1 participant had chronic obstructive pulmonary disease (COPD). Only three participants reported no symptoms of allergies, asthma, frequent respiratory infections, or COPD. However, no correlation was observed between participants that reported having some type of condition that may be associated with air quality and HAP use, and temperature remains the one factor with a clear relationship to use.

4 Discussion

The reduction in $PM_{2.5}$ seen in the work presented here, a mean of 45% after 90 minutes, is in line with those found in other studies. Spilak et al. [20] reported a reduction in $PM_{2.5}$ of 54.5% (median value) in locations using HEPA filtration in a crossover study in Denmark. An intervention study by Park et al. [17] showed a reduction in $PM_{2.5}$ of 43% when HEPA filtration was used. A modelling study by Fisk and Chan [41] simulated the indoor air for a number of scenarios including using portable air purifiers in homes without forced air systems, which closely resembles the typical conditions in London flats. They found in the modelled results that homes with continuously operating portable air purifiers had a reduction of 45% in $PM_{2.5}$ concentrations. In the work presented here, aggregated, normalised concentrations in the bedrooms, from the internal HAP sensors, show improvement of air quality when using the device. The median percentage reduction after 30 min was 20%, median percentage reduction after 60 min was 34%, and after 90 min a median reduction of 45% was seen. In 30% of cases, after the HAP had run for 30 minutes, concentrations had reduced from their initial concentration by at least 50%, and in 45% of cases after 60 min a reduction of at least 50% is seen. It is also worth noting that the actual running time of the air purifier is often longer than 100 minutes, especially in warmer weather (see Figure 3-6) which could lead to larger reductions for longer periods of time. However, there were also many occasions, either due to thermal conditions or perceived air quality, in which residents did not use their HAPs at all.

In this work, residents were generally dissatisfied with several aspects of their indoor environment. Perhaps most notably, 79% of respondents thought that the air was too still and 63% thought the air was ‘stuffy’ in the summer, conditions that could be correlated with inadequate ventilation, and therefore with higher levels of indoor air pollutants. Notably, levels of CO_2 in bedroom in the summer were relatively low and windows were operated frequently, suggesting that occupants’ perception of ‘stuffiness’ may have been a consequence of higher temperatures rather than perceived air quality. The perception of stuffiness would be supported by frequent high levels of measured CO_2 in the heating season, especially in bedrooms, indicating a low air exchange rate. However, only 27% of occupants reported dissatisfaction with the stuffiness of their homes in the winter. Additionally, 69% of the residents reported that it was too hot in the summer, with 68% of them saying that they were uncomfortable in the summer due to high temperatures. Given that so many occupants are dissatisfied with the thermal conditions in their homes, and that they reported that the HAP provided “cooling” (likely due to increased air movement caused by the device), it is not surprising that the greatest utilization of the HAPs was seen during the warmest weather. The combination of the residents’ perception that the quality of the indoor environment of their homes was more acceptable in the cooler months and that the air purifiers had a “cooling” or “freshening” effect, may have led the residents to use the air purifier less often, or inconsistently, in the heating months, irrespective of the actual air quality, as was demonstrated by the probability of HAP use illustrated in Figure 3-7. This low rate of HAP utilization during the heating season could lead to unacceptable indoor air quality. As people cannot directly perceive $PM_{2.5}$, or may otherwise prioritize thermal comfort, they may not respond appropriately to the actual risk of $PM_{2.5}$ exposure.

Even though many of the standards of practice for ventilation are based upon what is *perceived* as acceptable air quality by the vast majority of people, we know little about whether perception correlates with actual air quality. The evidence presented here indicates it does not, rather temperature was demonstrated as the most important determinant of air purifier use, irrespective of $PM_{2.5}$ concentrations. The perception of indoor air quality is influenced by many other factors including: relative humidity, noise, as well as the actual cleanliness of the air. Historically, bio-effluents from occupants were thought to be the primary pollutant of non-industrial spaces despite recognition that they posed little or no health risks (although we are coming to understand that carbon dioxide may impact cognitive performance), and dilution via ventilation (often at very high air exchange rates) was seen as the solution. In more recent times, the focus on reducing greenhouse gas emissions and improving energy efficiency has led to increased airtightness of buildings. The apartment buildings that were monitored in this research reflect this new approach to managing ventilation. Mechanical ventilation with heat recovery (with bypass in the non-heating season) is available for flats located at Site A, but it only includes minimal filtration (ISO coarse 45%), that is not adequate for the removal of $PM_{2.5}$. It is therefore up to the occupants to open or close windows, and the cleanliness of the outdoor air, to achieve satisfactory indoor air conditions. However, if occupants cannot perceive unacceptable $PM_{2.5}$ levels, or if other environmental conditions override their perception, they may not make the best decision in terms of exposure risk reduction. It is evident from the BUS instrument results and the monitored use patterns of the HAPs, that occupants are more responsive to changes in thermal conditions than to indoor air pollution.

There is very little published research on, or references made to, the operational behaviour towards air purifiers and the two studies that were found differed substantially in their findings. The participants in the work presented here reported that, in large measure, they did not use the HAPs for their intended benefit of reduction in particulate matter, but as cooling fans. This pattern of use could be problematic if in the cooler months, as is typical, window operation declines and indoor cooking activities and candle burning increase (i.e. indoor $PM_{2.5}$ sources increase). Surprisingly, we found no correlation between reported health conditions and HAP use, despite many of the participants saying in the baseline interviews that they were concerned about the impact of air pollution on their personal health. Pei et al.[31] proposed in their work that the substantial difference in the use patterns found in their study and those reported by Piazza et al.[32] was due to personal health motivations. Our findings do not support that supposition, but a larger scale study with unhealthy subjects and healthy controls would be useful in verifying the observations made here.

Further work is needed to understand if there is any connection between home air purifier use and improvements in health, as there is limited evidence found in the literature. However, a reduction in indoor $PM_{2.5}$ concentrations was clearly shown in this study as with others, and even small reductions in $PM_{2.5}$ exposure have demonstrated links to health benefits [42]. A potential factor of low HAP utilization (outside of the crossover period during which the use was directed) was the cost of electricity for operating the device. Many of the participants were receiving some level of housing support based on financial need, and some of them expressed concern about the cost of electricity, which although relatively small at approximately £2-3 per month (or between 3-5% of their monthly bill), was not negligible for some participants. This factor remains a limitation in our understanding of the motivations that could influence occupant behaviour. Another limitation of this study was the lack of a sham device. Participants were aware when the HAP was off, and may have believed, therefore, that the air quality was poor when it was not. An additional limitation of the work presented here was that the indoor air quality monitors were in a different room than the air purifiers. The monitors use a small fan that switched on and off periodically that was reported in the pre-trial tests as too disruptive to sleep. $PM_{2.5}$ was monitored in the bedrooms, however it was only via the HAPs' built-in sensors, which were uncalibrated and have limited resolution, although they were validated against other reference instruments with good agreement. A passive sampling method might be better suited to monitoring in bedrooms, and could complement other measurements. Additional research should be carried out over a longer study period, with a greater number of participants with a focus on specific disease outcomes. Monitoring exposure to a range of pollutants should also be included as part of future work, to better understand the levels and types of air pollutants people are subjected to, and if or how they are perceived. That being said, the results presented here are important because $PM_{2.5}$ is a pollutant of significant concern due to its demonstrated negative impact on health.

Commercially available home air purifiers do a good job of reducing $PM_{2.5}$ levels from the indoor air (in the rooms in which they are located), but if occupants fail to use them because of a misunderstanding of their utility or a misperception of risk, solutions that take humans out of the loop may be one approach to ensuring that the devices are working as intended and to their full capacity. However, as users generally prefer to have control over the equipment and may disable automation, providing better education and appropriate warning systems could be an alternative or additional strategy. Integrated sensors, default ON (user must opt-out of HAP use), and integration with ambient air quality data may also be options available to allow the HAPs to function more effectively to reduce $PM_{2.5}$. A study by Huang et al. [43] supports the use of integrated sensors, and automatic modes. In the study, when people operated their air purifiers on auto-mode, indoor $PM_{2.5}$ levels reduced by 40% compared to 28% for adjustable-mode.

5 Conclusions

The present study showed that $PM_{2.5}$ concentrations in bedrooms were reduced with HAP use. The mean reduction in concentration was 45% after 90 minutes of run time. The indoor $PM_{2.5}$ concentration tended to follow changes in outdoor $PM_{2.5}$, although generally at a lower level. There were peaks in $PM_{2.5}$ levels both indoors and outdoors in the morning and evening, reflecting rush hour traffic and predicted indoor activities.

Residents were generally dissatisfied with many of the conditions in their homes in summer, and thought temperatures were too hot and they did not have sufficient control over cooling, both of which may be affected by the use of air purifiers due to the fan-driven air. Poor air quality, however, can and does persist throughout the year, therefore other motivations need to be considered if air purifiers are to be used for year-round removal of particulate matter.

The use of portable air purifiers to reduce $PM_{2.5}$ could help to mitigate the negative health effects of exposure whilst at home, if occupant behaviour towards the devices could be better managed to reflect indoor air pollution levels rather than thermal conditions.

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