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Open or Closed? Use of Windows and Doors at Home: Ventilation Rates in Occupied Dwellings

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ABSTRACT

Ventilation in dwellings is likely to be impacted by configurations of windows and internal doors, but there is little empirical research investigating this in occupied homes. Closure of internal doors will affect noise, light, heat flow and how air moves into and through a building, as well as the volume of air in which pollutants are diluted. However, most ventilation measurements in homes have either conducted long-term averages in which the effect of use of windows and doors is not addressed, or small numbers of 'snap-shot' measurements in which the distribution of ventilation rates in particular configurations is not known; this reduces our understanding of environmental quality at home.

This paper reports the detailed investigation of window and internal door use and their link to ventilation measurements in two occupied flats in the same building over six months. Doors and windows were monitored using event-logging contact sensors and CO_2 was measured in all rooms. An algorithm for determining occupied periods was used and ventilation rates were estimated using the CO_2 decay technique during unoccupied times. In one of the flats almost 70% of the ventilation measurements were less than 0.5 ach in the configuration in which the occupant spends 55% of their time while at home; in the other flat windows were open for 80% of the occupied time and 90% of the ventilation rates measured with windows open were above 0.5 ach. The dwellings were physically similar, equipped with the same ventilation equipment and subject to the same weather. These results highlight the importance of considering the extent to which conditions during measurement periods (or modelled conditions) reflect the conditions that occupants experience.

Further research employing methods able to characterize ventilation in homes and distinguish between occupied and unoccupied times, contextualized by measuring configurations of doors and windows, will support greater understanding of ventilation in dwellings. This could provide insights into the real conditions in homes, supporting effecive modelling and design. Such detailed research would support developments in practice and policymaking, by helping to disentangle the related issues of ventilation rates, indoor pollution, personal exposure to pollutants and the effects of these on health outcomes.

INTRODUCTION

Countries around the world are committed to reducing their CO_2 emissions through the Paris Agreement (UNFCCC, 2015). Replacing indoor air with outdoor air is necessary to dilute and remove pollutants produced indoors, but excessive ventilation increases the energy required to condition the building (ASHRAE, 2013). However, there remain important gaps in our knowledge and measurement of ventilation in occupied dwellings.

There is an extensive literature on measurement of ventilation rates› in buildings using a variety of measurement methods. Ventilation is caused by indoor-outdoor pressure differences driven by (constantly changing) temperature

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difference and wind. However, most studies which have measured ventilation rates in homes have conducted very few repeat measurements, or have used long-term average based methods (Persily, 2016). An exception is Wallace *et al.* (2002) who used SF_6 decays to measure ventilation in an occupied home during a year, they found a mean ventilation rate of 0.65 h^{-1} and standard deviation of 0.56 h^{-1}, highlighting the considerable variability of ventilation. They identify a limitation in that the periods in which windows were open were not reliably recorded, presumably the same stands for internal doors although this is not discussed.

Window opening has received considerable attention in several areas of study. Fabi *et al.* (2012) reviewed the literature on drivers of occupant use of windows, finding that most research has focused on the effect of environmental conditions in office environments on window opening, they argue that further research in homes would be beneficial given the amount of time people spend in this environment. There are also many examples of studies modelling ventilation through windows, for example Wang *et al.* (2017) modelled ventilation through different styles of window, finding that this can make a significant difference to the ventilation. Measurement studies, such as Caciolo *et al.* (2011) have also attempted to empirically characterize ventilation through windows. Studies in these areas show that the effect on ventilation of window opening in a specific building will depend on the physical characteristics of the particular building, window and external environment (e.g. orientation, local shielding effects, weather), and the extent to which occupants experience this will depend on their use of windows (e.g. frequency, weather, degree of opening, etc).

The impact of internal doors on ventilation has received very little attention. However, Few *et al.* (2019) found that the ventilation rate in a single door-closed room was 0.5 h^{-1} lower than the whole dwelling, while Sharpe *et al.* (2015) found that 55% of their sample of 200 slept with the bedroom door closed. This could indicate a risk of low ventilation rates overnight for a large number of people. Occupant use of internal doors is also affected by, and will affect, a range of factors, such as light, noise and heat flow. Furthermore McDermott *et al.* (2010) investigated the use of self-closing fire doors in dwellings and found that these were propped open for a range of reasons including watching over children and preventing finger-trapping in doors, indicating a range of social reasons for arrangements of door opening in homes.

The lack of extended ventilation measurement campaigns distinguishing between different configurations of doors and windows, together with limited understanding of internal door and window use, combine to represent a lack of empirical understanding of the ventilation experienced by occupants at home. This paper seeks to explore some of these issues by presenting the findings from two occupied dwellings in which ventilation rates and door and window use were measured. The following sections present the methods employed, followed by the results of observed times in different configurations of open and closed doors and windows, and the ventilation rates measured in those configurations. Finally, the limitations and implications of the method and results are discussed.

METHODS

Results are presented from two flats in the same building located in London, England. The building was constructed as an office in the 1980's and refurbished into a block of over 100 residential flats in 2015. Each dwelling was equipped with a continuous centralized mechanical extract ventilation (MEV) system and at least 7500 mm^2 equivalent area of trickle ventilation. In both cases the trickle vents were closed as found and the occupants were not asked to adjust the vents during the measurement period so that the ventilation ordinarily experienced by the occupants was measured. Both flats had a floor area approximately of 40 m^2; one bedroom, a combined kitchen-living room and bathroom all connected by doors to a hallway. Both bedrooms had one window, Flat A had two living room windows (three openings) and Flat D had four living room windows (seven openings due to three double casement windows) – one located close to the kitchen area and the other three in the living room area. The windows were all tip and tilt type, with both households almost exclusively using the tip function (pivoting at the bottom with a maximum opening of 10 cm). Flat A was single aspect, while Flat D was dual aspect with the bedroom, kitchen and living room window 1 on the same façade and the remaining windows on the perpendicular façade.

Measurements took place from June 2019 until January 2020. Eltek GD-47 sensors recorded CO_2 concentration, temperature and relative humidity every five minutes externally and in all rooms except the bathroom. Sensors were placed between 1.0 and 1.5 m above floor on surfaces such as tables and counter-tops outside the breathing zone of the occupants and away from heat sources. HOBO-UX100-01 event-logging magnetic proximity sensors were placed on all doors and almost all windows (only one side of the double casement windows in Flat D were monitored) such that they would record an open event when the window was tipped or tilted open. The degree of opening was not measured.

Ventilation Measurement and Occupancy Algorithm

This research used the CO_2 tracer decay method, which has been widely used for ventilation measurement (Persily, 2016). Metabolic CO_2 produced by the participants was used as the tracer gas, this likely increases the participant acceptance of the method since less equipment is needed than for methods requiring gas to be artificially introduced, this was a key motivation for the original development of the technique (Penman and Rashid, 1982).

In order to make use of this method it is necessary to accurately determine when the space is unoccupied, but the ventilation literature provides limited examples for achieving this. Few and Elwell (2019) presented an algorithm which uses window and door opening data with CO_2 concentration to establish when the dwelling is unoccupied, this was used to split the monitored data into occupied and unoccupied datasets. The total, occupied and unoccupied time each flat spent with individual configurations of windows and doors was then calculated.

Within the unoccupied dataset, periods of decaying CO_2 concentration difference (ΔCO_2) were used to calculate the ventilation rate. Only decays in which ΔCO_2 measured in all rooms was within 10% or 50 ppm are presented, further details are given in Few (2021). At these times, air in the dwellings can be considered to be a uniform single zone, with the measurement interpreted as the whole dwelling ventilation rate. If internal doors had been closed then it is likely that the space would not behave as a single zone and this method would have been inappropriate, however in the monitored flats doors were never closed during unoccupied periods. The mean uncertainty of the calculated ventilation rates was 13% for Flat A and 12% for Flat D, see Few (2021) for further details. The configuration of doors and windows for each decay period was recorded. The following section presents the results from this analysis.

RESULTS & DISCUSSION

The results from Flat A are presented in Figure 1 and Flat B in Figure 2, the key for the abbreviated title of each row of results is given in Table 1. Two features of the results particularly illustrate the ability of the methods and analysis to give insight into the way in which occupants interact with their doors and windows and how this relates to the ventilation in the space.

Firstly, all windows are closed for 20% of the occupied time and less than 5% of the unoccupied time in Flat A (Figure 1 - WO: None; DO: All). Only three ventilation measurements were taken in this configuration, but all were below 0.5 h^{-1}, which is often considered a threshold for adequate ventilation (Dimitroulopoulou, 2012). The vast majority of the ventilation rates measured in all other configurations were over 0.5 h^{-1} (accounting for the configurations during 80% of the occupied time), at least one window was open in all these configurations. The occupants may be at increased risk of poor indoor air quality during the 20% of time in which they are at home with windows closed; the impact on the occupants depends on the pollutant sources during these times. This finding illustrates the potential value of a method that disaggregates ventilation rates at different times, can associate them with occupancy and window and door opening practices and can be implemented over extended monitoring periods.

Secondly, the results from Flat D show that 55% of the occupied time takes place with all internal doors open and all windows closed (WO: None; DO: All). Almost 70% of ventilation rates measured in this configuration are below 0.5 h^{-1}, so the occupant may frequently be experiencing inadequate ventilation at home. The second configuration in which the occupant spends significant amount of time, generally overnight, is with the bedroom door and all windows closed (WO: None; DO: Liv-Bath). It is likely that the ventilation rate in the bedroom during these times is different to the ventilation rate with all doors open due to the changes in airflow throughout the flat (Few *et al.*, 2019). Whilst the ventilation in these times could be relevant to occupant sleep quality and next-day performance (Strøm-Tejsen *et al.*, 2016), it was not possible to determine the distribution of ventilation rates in this configuration, as discussed below.

Although the two flats presented here were physically very similar, located in the same building, and were equipped with the same continuous MEV systems, they were operated extremely differently resulting in considerably different ventilation rates measured in each dwelling. Flat D was almost always reliant on the continuous MEV system to provide adequate ventilation and low ventilation was often observed in this configuration, whereas Flat A almost always had windows open and measured ventilation rates were almost always above 0.5 h^{-1}. Together these results show that in order to understand the ventilation conditions people experience it is necessary to attend to the use of doors and windows, the periods in which the occupants are present and the variability of ventilation over time. The implications of these findings are discussed after the limitations associated with the method are addressed in the following section.

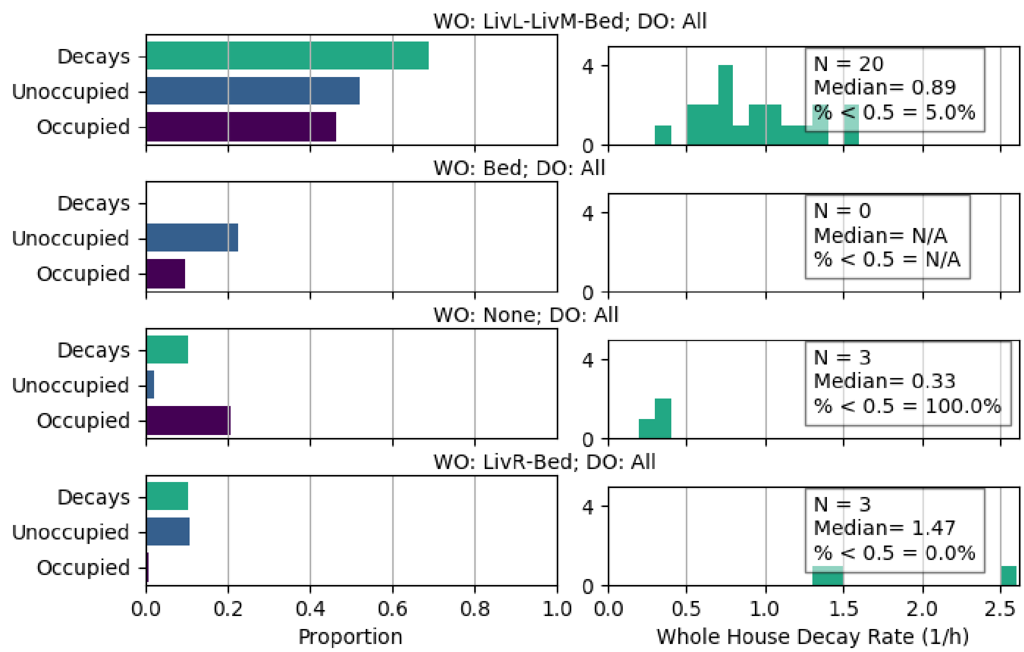

Figure 1. Summary of results for Flat A. Each row represents a different configuration of doors and windows – the abbreviated descriptions for each row are explained in Table 1. Bar charts on the left show the proportion of ΔCO_2 decays measured in Flat A for each configuration, and the proportion of occupied and unoccupied time that the flat spent in each configuration. The histograms on the right show the ventilation rates calculated from the decays in each configuration, and the boxes show the number of measurements, the median ventilation rate (h^{-1}) and the percentage of measurements which were lower than 0.5 h^{-1} for each configuration.

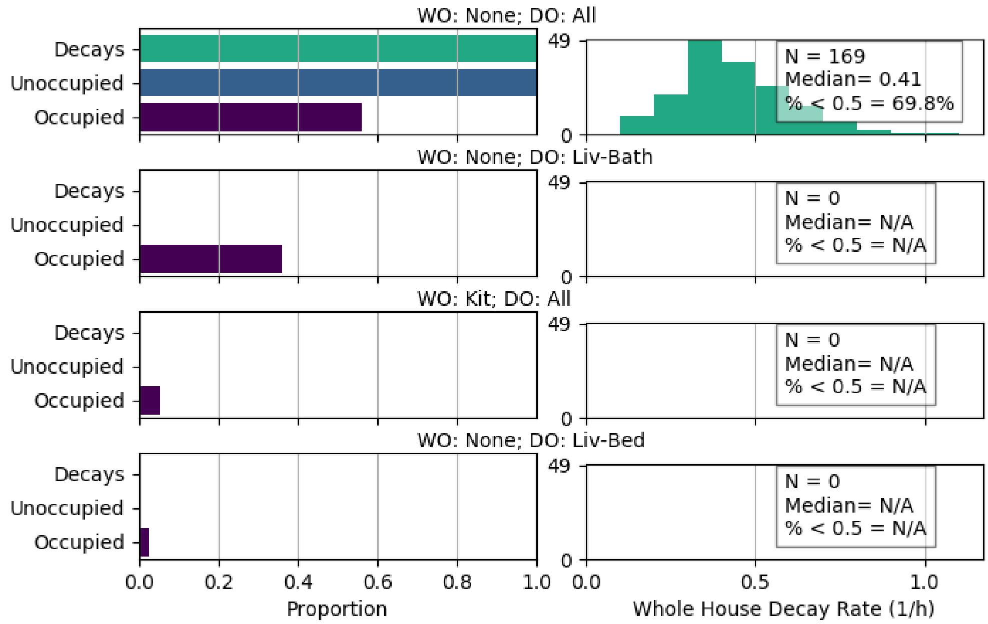

Figure 2 Summary of results for Flat D. Each row represents a different configuration of doors and windows – the abbreviated descriptions for each row are explained in Table 1. Bar charts on the left show the proportion of ΔCO_2 decays measured in Flat D for each configuration, and the proportion of occupied and unoccupied time that the flat spent in each configuration. The histograms on the right show the ventilation rates calculated from the decays in each configuration, and the boxes show the number of measurements, the median ventilation rate (h^{-1}) and the percentage of measurements which were lower than 0.5 h^{-1} for each configuration.

Table 1. Key for Figure 1 and Figure 2 abbreviations

Abbreviation	Explanation	Abbreviation	Explanation
WO	Windows Open	Bath	Bathroom
DO	Internal doors Open	Liv	Living Room
Bed	Bedroom	L/M/R	Left / Middle / Right Window

Limitations

As with all methods, the technique presented here is subject to a range of limitations. Firstly, this was a natural experiment, so only those configurations in which the occupants arrange the dwelling are observed, and the ventilation rate is only measured in unoccupied configurations. The results for Flat D show that only three configurations are used by the occupants, enabling ventilation rates to be estimated for configurations relevant to those experienced. However, it was not possible to estimate the ventilation rate experienced in the bedroom overnight as the dwelling was never left unoccupied in that configuration (WO: None; DO: Liv-Bath). The overnight bedroom ventilation rate could have been estimated using the CO_2 build-up method. Whilst many authors have estimated the CO_2 generation rate of occupants while sleeping, prior to Persily and de Jonge (2017) this was frequently undertaken using generic estimates not adjusted according to the weight, height, age and gender of the participants. Accounting for these parameters can result in a 60% variation in the CO_2 generation rate between participants, and even for the same participant a metabolic rate may vary 10-15% day-to-day when performing the same activity (Parker and West, 1973). This suggests that the method will give results with large uncertainty.

Sharpe (2019) argues that we must be more aware of the ethical aspects of post-occupancy research in buildings, and there is an ethical dimension to consider here. Participants may from time to time have overnight guests, and in analyzing the CO_2 generation rates it is necessary to know or estimate how many people are present in the dwelling. We consider it a significant invasion of privacy to do this, not justified by the highly uncertain result that would be obtained. Instead, the method could be supplemented by undertaking some targeted experiments, to gather relevant data from particular door and window configurations when similar situations arise. Such work relies on a willing participant, and in this case was not possible.

Finally, whilst the presented method enables either the estimation of a distribution of ventilation rates or of a ventilation rate in similar conditions to a specific occupied period, it does not estimate the ventilation rate during occupied periods. Ventilation will be influenced by the use of mechanical ventilation, temperature difference, wind speed and direction (ASHRAE, 2013), but previous research investigating multiple measurements of ventilation rate in the same building have often struggled to find strong relationships between these parameters (Wallace *et al.* 2002). Sinden (1978) performs several thought experiments which illustrate the complex interaction of wind and temperature. However, if the distribution of environmental conditions during measurement periods is similar to that during occupied times, then the measured ventilation distributions are likely to be an appropriate reflection of the distribution of ventilation experienced during occupied times for each specific door and window configuration. Relating the measured ventilation rates to different window and door configurations enables a link to be drawn and insights developed between the occupant practices and conditions experienced.

Implications of the Findings

Implications for Health. Fisk (2018) systematically reviewed the literature regarding the effect of ventilation on health and concluded that the evidence suggests that increased ventilation rate is associated with better health outcomes, although it was not possible to identify a threshold ventilation rate at which this happens. Fisk identifies that the studies reviewed used inconsistent ventilation metrics such as ventilation per person, per floor area or air changes per hour and that this complicated the analysis. From the results presented here it additionally seems plausible that the reduction to a single value of many different ventilation rates experienced in different configurations of windows and doors during occupied and unoccupied times could also be a confounding variable. For example, a difference in configuration of door and window opening when occupied than when unoccupied could lead to significant differences in ventilation rate, but only the former is likely to have health implications. A method that enables the characterisation of door and window configurations during occupied and unoccupied periods, and then links this to ventilation rates observed in those configurations, may enable greater insight into the impact of ventilation rates on health outcomes.

More work to disentangle ventilation, pollutant sources, occupant locations and exposure time may be beneficial. McGrath *et al.* (2017) modelled personal exposure to indoor pollutants for different occupants with various indoor pollution location and source strength profiles, door closures and occupant location profiles, finding that some occupants were exposed to significantly worse pollution than others in the same dwelling. Their profiles of occupant locations were to an extent based on time of use surveys, but more work such as that presented here could help to understand the use of internal doors, windows and ventilation rates in different configurations so that such studies can better represent as-occupied conditions.

Implications for Policy. In England, research undertaken to assess ventilation in homes complying with building regulations has relied on perfluorocarbon tracer gas methods, typically averaged over one week (DCLG, 2010; MHCLG, 2019). While this gives an impression of the average conditions in the space, it may be helpful to combine this with a more detailed understanding of the conditions in occupied homes. The method presented here, characterising door and window opening practices and associated ventilation rates, may be used to gather evidence of the varying conditions experienced by occupants in support of the development of policies to improve conditions in dwellings.

Implications for Research. The combination of long-term monitoring, measurement and analysis methods used here is a promising tool for further research. At present it is unusual to collect data over an extended period to enable characterisation of the use of doors and windows, and the associated ventilation rates. Gathering these results, that represent the ventilation over a wide range of external conditions, using controlled experimental methods would have required considerable research time and equipment, and much greater burden to participants if taking place in an occupied dwelling. More research that investigates the ventilation rates experienced in occupied dwellings will provide the empirical evidence to support improvements to policy and practice to deliver healthy living environments at low energy cost. Such evidence also cross-references and provides input data to models of ventilation performance, for the operation of test dwellings and laboratory testing. Increased availability and ease of verification and testing in real dwellings would clearly be helpful for ensuring models of ventilation, and its consequent effect on IAQ, target the most relevant dwelling configurations for different households.

Finally, whilst it is expected that internal door and window opening will have a significant impact on ventilation rates, there is little empirical research that addresses this. Further research will help to characterise the impact of window and door opening, and how this is managed by different occupants, and identify ways in which homes can perform better for occupants. It would also help inform modelling studies which assess personal exposures dependent on door use and pollutant locations.

CONCLUSION

This paper has presented data from a 6-month monitoring campaign in two occupied homes. It is common for ventilation measurements in occupied homes to either make use of long-term averaging methods or to conduct a small number of ‘snap-shot’ measurements. However, this monitoring campaign aimed to characterise the ventilation of test properties over an extended period of time, exposed to changing external conditions and subject to real occupancy. Detailed door and window monitoring was undertaken alongside use of an algorithm for determining periods of occupancy, and the ΔCO_2 decay method was used in unoccupied periods to calculate ventilation rates. Insights into the operation of doors and windows has been possible, combined with measurement of a distribution of ventilation rates measured in these configurations. This level of detail would have been extremely resource intensive and invasive for occupants if controlled experiments had taken place instead.

The analysis revealed significant differences between the conditions in the two monitored flats. Flat A had at least one open window for over 80% of the occupied time (continuing through the monitored winter period), the vast majority of measurements in these configurations were above 0.5 h^{-1}. Whereas Flat D very rarely opened windows and 70% of the ventilation rates measured in the most common configuration were below 0.5 h^{-1}. Although the flats were located in the same building and equipped with the same ventilation equipment, the ventilation rates the occupants experience are shown to be significantly different.

Measurement of ventilation in the changing conditions of occupied homes will improve our understanding of how occupants interact with their homes and the effect of this on the ventilation conditions they experience. Such research will improve assumptions in models of ventilation and pollution exposure as well as providing an experimental comparison for modelled results. This would also help us to understand not just the theoretical conditions in perfectly-built homes, but the conditions in homes as-built.

Finally, there are potential health implications to the ventilation rates people experience in their homes, most obviously in the way in which they relate to personal exposures to pollutants. Current research attempting to characterize the relationship between ventilation rate and health has treated ventilation in the home as though it is a single value, while the results presented here show that people are experiencing a wide variety of different ventilation rates depending on the configuration of doors and windows, the weather and the location of the occupants within the dwelling. Neglecting this level of complexity may contribute to the lack of clear relationship between health and ventilation that are generally reported. Further work to unpick the combined issues of ventilation rate under different configurations, pollutant sources and occupant locations may help to provide a more coherent understanding of the link between ventilation and health.

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