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Natural ventilation in damp homes – a qualitative exploration of behaviours and interventions for change

Dr Caroline Halley, Dr Elinor Chisholm, Prof Michael Keall, Dr Julie Bennett

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1222 Moonshine Rd, RD1, Porirua 5381
Private Bag 50 908, Porirua 5240
New Zealand
branz.nz

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Report prepared for Building Research Association of New Zealand

Dr Caroline Halley, Dr Elinor Chisholm, Prof Michael Keall & Dr Julie Bennett

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A. Executive summary

Ventilation behaviour in Aotearoa New Zealand (NZ) is an under researched area, despite the benefits that ventilation may have on occupant respiratory health. Most NZ homes rely on natural ventilation, i.e. window opening, which in turn relies on occupants to control ventilation. To understand how and to what extent people ventilate their homes, and ways in which ventilation can be improved, we carried out four studies on ventilation behaviour.

Firstly, we explored previously collected data from 450 Wellington households in the Health of Occupants of Mouldy Environments studies, to examine mould levels, temperature and relative humidity in relation to ventilation behaviour patterns. A daily pattern of opening bedroom windows in winter was associated with a reduced amount of visible mould compared to rarely or never opening the windows. Alongside ventilation, winter sunshine levels appear to be particularly important in reducing mould. Other factors that led to less mould included increasing the warmth in the room (nighttime heating the bedroom) or reducing condensation (double glazing, newer houses with better insulation levels), or lower house occupancy (less moisture generation via respiration, laundry, bathing and cooking activities). Interestingly bathroom ventilation was not found to be associated with the levels of mould in the child's bedroom, suggesting localisation of mould by room, and that factors more directly associated with the bedroom environment have a greater impact on mould growth.

There were high reported levels of ventilation during cooking and showering/bathing activities, with mechanical ventilation (extractor fans/rangehoods) favoured over window opening. Very few houses had no form of ventilation in these areas. The high level of reported clothes drying indoors was concerning and may be one area to target to reduce the accumulation of moisture in homes. Limitations to the study included that the geographic area studied was small and the results may therefore not be applicable to all climatic areas of New Zealand. Data was not collected on outdoor temperature, and information was not gathered on length of time windows were opened or what the barriers to ventilation might have been (i.e. security concerns, shortage of time).

A second study examined whether giving written advice on ventilation and mould removal alongside provision of heating could reduce mould in children's bedrooms over an eight week period during autumn to spring. The study was conducted in the wider Wellington region in 152 participants' homes and compared to 149 control homes. The study found that there was no significant reduction in observed mould levels between the intervention and control homes, suggesting that these activities alone may not be enough to reduce mould in a bedroom.

To deepen our understanding of ventilation behaviour in homes qualitative interviews were conducted with housing assessors (n=5) and with whānau (n=28) living in homes with potential dampness issues. Three key themes arose from these interviews. First, years of experience of living in damp housing created high levels of "damp intelligence" which was awareness of why the dwelling was damp, what could be done to address the problems caused by damp housing and ways to minimise moisture in homes. This intelligence was generally consistent between assessors and occupants, however an exception was the length of time windows were opened for, with assessors suggesting wide opening for a short time once or twice a day, compared to occupants opening partially for the whole day, or a large proportion of the day. The second theme to emerge from the interviews was that living in damp housing degrades quality of life, impacting people's comfort and health, and costing occupants time, labour, and money. The third theme was that despite their extensive knowledge about managing moisture, occupants living in damp housing were often hampered in their ability to reduce dampness because of deficiencies in the dwelling's structure or fittings, as well as the cost, inconvenience and labour associated with exercising some of the moisture and mould-reduction strategies. Assessors reported that these issues affected their clients' ability to improve the indoor air environment as well; however, they were able to recommend workarounds and provide information based on their clients' particular situation, which could sometimes overcome those impediments.

Our final study piloted and evaluated a low-cost intervention aimed at improving ventilation behaviours. An air quality monitor was temporarily installed on a shelf or wall (1.2 – 1.8m) in a bedroom or living room area, for a four-week period between July to September 2023 in 20 households, who were recruited through community groups and Facebook pages. For the first two weeks participants received no information from the monitor (a baseline period) and for the second two weeks, they received information about temperature, relative humidity, carbon dioxide, volatile organic compounds, light intensity and noise via the screen on the monitor, and for those who set it up, via an app on their cell phone. Alerts about conditions that were sub-optimal were sent to cell phones, as well as appearing on the monitor screen. The pilot demonstrated that use of air quality monitors in homes is a feasible intervention. The monitors were generally well received by occupants and the units themselves were easy to set up, had an excellent screen interface, alert levels could be readily changed, and there were no interruptions in data collection using the Internet of Things (IoT. Participants found the data useful, with many reporting that they opened the windows more or heated the room more than they would otherwise have. Some found the sensor was validated concerns about the cold and damp issues in the home, while others were reassured that their home conditions were not as bad as they had feared. The use of 'percentage of time household is in optimum conditions' gave an effective overview of the house conditions. The app could be improved by showing participants a graph of the last 24 hours of data, rather than just the one hour that is currently provided. Limitations to the study included that the intervention was conducted in a small number of homes, for a small timeframe (two weeks), and would need to be carried out in a larger number of homes for a longer time frame to reasonably be expected to impact indoor mould levels. Habituation to alerts would need further investigation in a longer trial, although it is hoped that behavioural change may be achieved before that occurred. There may also be a limit to what is achievable given some of the constraints reported by participants, such as heating costs, deficiencies in the dwelling's structure, and willingness to carry out daily ventilation.

This research has demonstrated that occupant ventilation behaviour can influence the amount of mould in homes, and that ventilation is one key factor in keeping homes healthy. Our research has investigated and recommends several potential interventions that may lead to improved ventilation practices in a home. Written advice alongside heating for eight weeks in cooler seasons was not sufficient to reduce mould levels. Indoor air quality monitors may provide a helpful prompt to change ventilation behaviour, however ventilation behaviour can be complex, and be influenced by environmental and individual constraints that may make it difficult to follow best practice advice, or have that advice improve the conditions of a home. Tailored advice aimed at engaging with people's actual situations and overcoming individual impediments to ventilation may be useful.

Acknowledgements

Funding was received from the Health Research Council of New Zealand and Building Research of New Zealand (BRANZ) for this study. We thank Phillipa Barnes, Janice Kang and Julie Cooper for their assistance with visiting participants and gathering data. We thank Sustainability Trust, K'aute Pasifika, Renters United and Brodie Fraser for their assistance with participant recruitment. We thank Manfred Plagmann (BRANZ) for feedback on our interview schedules. We would also like to thank AirSuite for providing the air quality monitors for the intervention pilot study. Finally, we are grateful to all our participants in the described studies (numbering over 780 people), agreeing to take part in our interviews, giving their time, having equipment in their homes and for sharing their insights and experiences.

B. Introduction

"Open the window of your mind. Allow the fresh air, new lights and new truths to enter."
— **Amit Ray**

New Zealand houses are often larger, older, less well constructed and lack insulation compared to houses in other countries with similar climates (Howden-Chapman et al. 2009). As a result, our housing can be cold, damp and prone to mould growth, factors which have been associated with poor respiratory health for occupants (Fyfe et al. 2020; Ingham et al. 2019; Shorter et al. 2018).

The 2018 census, which included questions on dampness and mould, indicated that 318,891 NZ homes were affected by dampness (20% of homes). The census also indicated that 12.4% of owned 8.5% of family trust homes, and 28% of rental homes sometimes or always had mould larger than an A4 piece of paper.

Ventilating indoor environments has the potential to reduce indoor humidity and reduce mould levels, in situations where the outdoor air holds less moisture than the indoor air, which occurs for most climatic zones in New Zealand over winter months. However, domestic ventilation behaviours in New Zealand are under researched, despite the benefits that ventilation may have on occupant respiratory health. Most New Zealand homes rely on natural ventilation, i.e. window opening, which in turn relies on occupants to control ventilation.

Ventilation behaviour is poorly understood, and most ventilation research has focused on modelling behaviour based on thermal indoor/outdoor environment, from an energy use perspective, which can result in large discrepancies between energy use predictions and actual energy use (Andersen et al. 2013). Research on behaviours has predominantly occurred in office buildings and schools, with just a handful of studies, largely from Scandinavia, looking at domestic ventilation practices (Fisk et al. 2018). Previous research on ventilation in New Zealand has also predominantly concentrated on modelling, with a particular focus on thermal comfort and building performance (e.g. Pokhrel et al. in 2017). Given the potential benefits that may be gained by improving domestic ventilation, it is critical that we gain more understanding of how New Zealanders ventilate their homes, their understanding of ventilation, and whether there are barriers to ventilation practices.

To understand how and to what extent people ventilate their homes, and ways in which ventilation can be improved, we carried out a three-stage project. Firstly, we explored previously collected data from participants across Health Research Council (HRC) funded studies, to identify the patterns of ventilation and housing/household characteristics that are associated with reduced indoor humidity and low indoor mould levels. Secondly, we deepened our understanding of ventilation behaviour in homes by conducting qualitative interviews with housing assessors and with whānau living in homes with potential dampness issues. Lastly, using the knowledge gained, we piloted and evaluated a low-cost intervention aimed at improving ventilation behaviours.

C. Methods

Please note: All equipment was selected by the researchers involved in each project based on factors such as accessibility, technical specifications and expertise, and should not be seen as an endorsement of any specific brand.

Study 1: What factors of ventilation change mould levels in bedrooms? Health of Occupants of Mouldy Environments (HOME) study

A matched case-control study was conducted involving 150 case children with new-onset wheezing and 300 control children and a range of indoor dampness measures in 2009 – 2012 (Shorter et al. 2018). The study was conducted on children (aged two – seven years) from the wider Wellington region (Kāpiti, Wellington, Lower Hutt & Upper Hutt). Case children had had their first episode for wheeze in the previous 12 months, had received and take a medication for wheeze, and had lived in the same home for at least six months prior to developing wheeze. Control children, who were matched to each case child by area (nearest regional council), age (±6 months of the wheezing child) and sex assigned at birth. Parents or caregivers of potential participating children were sent a letter and an information pack on behalf of their GP inviting them to participate in the study.

For participating families, each home was visited by researchers on two occasions during autumn, winter or spring, four weeks apart. A researcher trained in mycology assessed condensation, visible water damage/leaks, mould odour, and visible mould in seven locations in the child's bedroom: bedroom walls, ceilings, floors, windows, curtains, bedding, and wardrobe areas. A scale for mould extent (0-3) was developed, which categorized visible mould for each area: none, small, moderate, or large/extensive using a showcard (Figure 1).

Researcher observations and severity of mould in the children's bedroom were totalled across the seven locations in each child's bedroom to give a researcher a mould score, with a minimum score of 0 (no mould) and a maximum of 21 (extensive areas of mould in all seven locations) possible. Temperature and humidity were recorded every 10 minutes over a 4-week period using an i-button data logger (DS1923-F5;Maxim Integrated™, San Jose, CA, USA). A building inspector also assessed the homes using a modified version of the Healthy Housing Index (Keall et al. 2007) to gather data on window size, ventilation, and insulation levels, amongst other markers.

Parents were asked questions about the children's and families' health and household characteristics such as household size, age of house, condensation, mould levels, and heating. Questionnaire responses were collected on ventilation frequency during summer and winter in children's bedrooms and living areas, use of kitchen and bathroom windows and extractor fans during moisture creation activities, how washing was dried in the household, number of openable windows, double glazing levels, in-home ventilation use and how much sun the child's bedroom received during winter. The study protocol was approved by the central health and disabilities ethics committee (HDEC CEN-09-06-039)

Statistical analysis was conducted using a multinomial proportional odds model assessed associations between mould extent scale (as an outcome) and ventilation frequency, number of occupants and tenure type, controlling for case-control status.

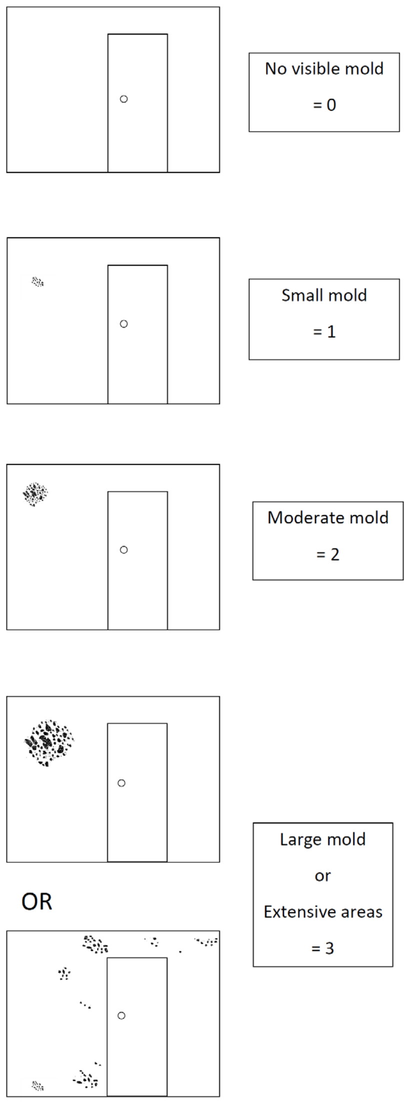


Figure 1: Mould severity scale (from Shorter et al. 2018).

Study 2: Can receiving heating and best practice advice reduce mould levels in children's bedrooms? RHINO study

A trial of bedroom heating was conducted in residential detached dwellings in the Wellington region, New Zealand (Walker et al., 2019, Shorter et al. 2022). Families were supplied with identical models of a heater to heat their child's bedroom overnight (n=152), during an 8-week period between April to November, with 63 families enrolled in 2013 and 93 in 2014. The thermostatically controlled electric heaters (Dimplex Cadiz eco CDE2ECC micathermic) were installed in children's bedrooms with a power use meter, at least 50 cm away from walls and other furniture. Parents were asked to use the installed heaters as the primary source of heating in their children's bedrooms, and to switch off any other heaters in the bedrooms, where possible. Timers on the heaters were set to come on 30 minutes prior to the child's bedtime and switch off 30 minutes prior to the child's expected waking time. These times were anticipated to cover most of the period the child was present in their bedroom, as well as the coldest daily temperatures. Temperature and humidity sensors (ibutton DS1923) were placed on an adjacent wall at a height of 1.5 m (±0.2 m) and set to take a reading every 20 minutes throughout the eight-week study period. Heaters were initially set to 20◦C or 21◦C, however parents were given the option of adjusting this temperature to a lower or higher level, if comfort levels required, as long as it was not set lower than 18◦C.

To remove potential economic barriers to heating, families were reimbursed for any power used. As part of the heating intervention parents were also given a detailed information sheet about best practice ventilation, mould removal and indoor moisture reduction advice. A comparison group (n=149) received no heater or advice sheet during the eight-week study period. As per the HOME study, each home was visited by a researcher who assessed visible mould in seven locations in the child's bedroom using a mould extent scale (0-3) for each location, categorizing visible mould into a mould score (0-21) for the bedroom (Shorter et al. 2018). The mould score assessment was carried out twice, at installation/parent interview stage and then again eight weeks later at the conclusion of the study.

Statistical analysis included logistic regression estimated the odds of improved mould scores over the period studied for the treatment group vs. the controls. Ethical approval was received from the Health and Disability Ethics Committee (HDEC 12/CEN/60).

Study 3: What are peoples ventilation practices, beliefs, and barriers?

We carried out 33 interviews: five with housing assessors, and 28 with people living in damp housing. The interview schedules were based on the study's aims and the existing literature. Interviews were open-ended and minimally structured, allowing the interviewer to stay focussed on the research questions while allowing for participants to articulate their perspectives freely (Liamputtong, 2013). Participants were sent the information sheet and consent form in advance. Prior to commencing the interview, consent was discussed and gained from all participants. All interviews were audio-recorded with the permission of the participant.

Interviews with housing assessors (n=5). Housing assessors were recruited through an existing research partnership with the Healthy Housing Initiative (the HHI). In this programme, people with children at risk of housing-related illness are offered a visit by a housing assessor, lasting approximately one hour, to talk about how they can improve their housing environment. Housing assessors provide some interventions, such as draught stoppers and heaters, and provide education on heating and ventilation, and may refer to other services, such as the curtain bank. Housing assessors are trained by the HHI programme and tend to have previously worked in health or in energy or building assessment. As they work with many people living in damp housing, they are well placed to comment on typical ventilation practices and barriers and enablers to address damp housing. The interviews took place over videoconference or in person and were audio-recorded.

Interviews with people living in damp housing (n=28). These participants were recruited via email lists and community groups (Renters United, K'aute Pasifika, a Hamilton-based social services organisation, and Well Homes, Wellington's HHI). Those recruited via email self-identified as living in damp housing. Those recruited via K'aute Pasifika and Well Homes were identified by their caseworker as having experience of living in damp housing. Two people, a couple who lived together, were interviewed together; other participants were interviewed by themselves. The interviews took place over the phone and lasted between 30 minutes and two hours. Participants were provided with a $50 voucher as thanks for their time.

The interviews were transcribed and coded for themes using a type of thematic analysis known as template analysis (Brooks et al. 2015, Crabtree and Miller 1992, King 2004). In template analysis, the researcher defines a template, or series of codes, prior to in-depth analysis of the data, and then adjusts these, adding and taking away codes, on multiple readings of the text. A code is "a label attached to a section of text to index it as relating to a theme or issue in the data which the researcher has identified as important to his or her interpretation" (King, 2004, p. 257). Initial codes may be determined by a preliminary scanning of the text, or by theoretical considerations. The subsequent template enables researchers to represent relationships between codes. This allows the codes texts to be read together, enabling the researcher to develop key themes.

In this project, a priori codes were based on the research aims and the resultant interview schedule. The template was continuously revised through multiple readings of the text, with additional codes developed and added to the template. This method is often used for applied research such as this study, as the use of a structured coding frame is ideally suited for producing results that fulfil pre-determined information needs, while still enabling unexpected codes and themes to emerge through the template revision process (Braun and Clarke 2021, King 2004).

Ethical approval was received from The University of Otago Human Ethics Committee (application 23/026).

Study 4: Can smart monitor technology change ventilation behaviour? Pilot study

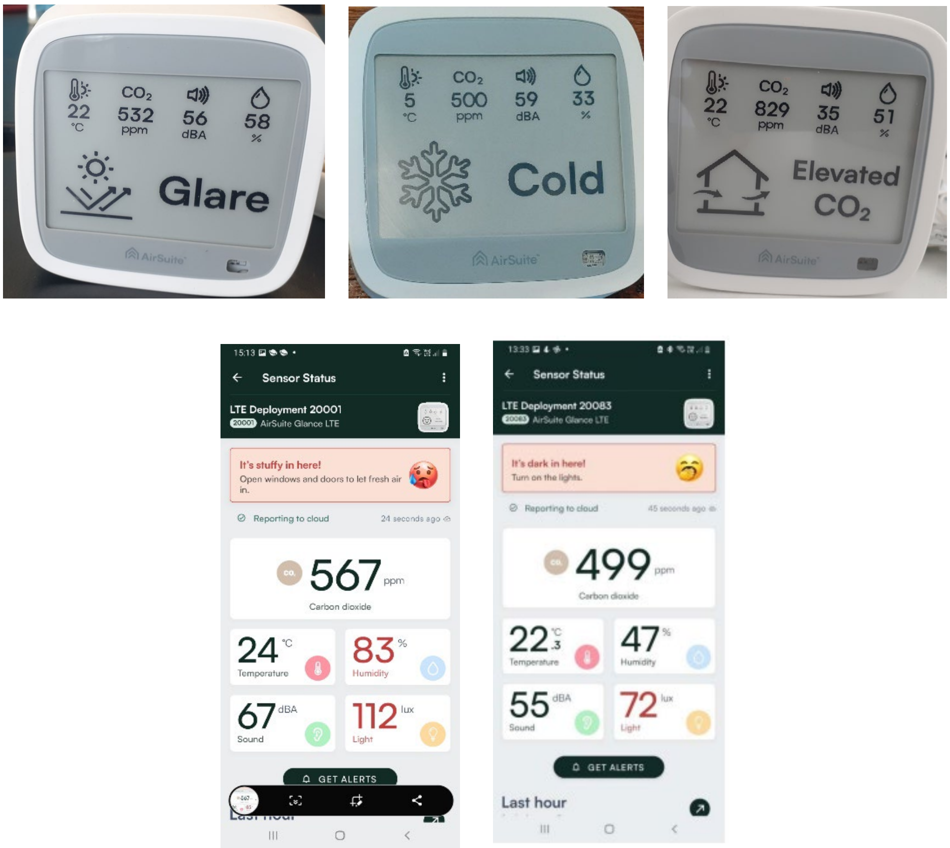
Twenty households, including 13 of those interviewed as part of Study 3, were recruited from community groups and email lists to pilot an indoor air quality monitor. The monitor was temporarily installed on a shelf or wall (1.2 – 1.8m) in a bedroom or living room area, for a four-week period between July to September 2023. The monitor (Picture 1) contained sensors for carbon dioxide (CO_2), temperature, relative humidity, sound, light, air pressure and volatile organic compounds (VOC). The sensors ran on battery and had a wireless connection which collected data remotely via Spark Internet of Things (IoT) network to a central cloud.

(A) (B)

Picture 1: Air quality monitor display (A) and with masking tape applied to cover the screen (B)

For the first two weeks after installation, a masking tape cover prevented participants from seeing the monitor screen. After two weeks a text message and an email was sent to participants instructing them to remove the tape, and also install a cell phone application to link to the monitor. Both the monitor screen and the cell phone app provided feedback to participants with suggested ventilation actions (Picture 2) when deviated from an optimal range.

Thresholds were set to alert participants if; temperature was below 16°C or over 25°C, relative humidity was below 40% or over 70%, CO_2 was over 1000 ppm, total volatile organic compounds were over 500 ppb, sound was over 70 dBA, and light was under 200 lux or over 1000 lux. Light and sound were not part of the research focus but were already installed in the monitor.



Picture 2: Examples of alerts and app information

At this time point participants were also provided with a factsheet (Picture 3) with tips about ventilation and how to reduce moisture in the home. As per the previous studies a researcher carried out a visual mould assessment in seven locations in the room using a mould extent scale (0-3) for each location and categorizing visible mould into a mould score (0-21) for the bedroom (Shorter et al. 2018). The mould score assessment was carried out twice, at installation/parent interview stage and then again four weeks later, when the monitor was removed. Interviews about participant experiences of the air quality monitor system were conducted after the four-week period (n=17). Data were collected on the percentage of time that households spent in the optimal ranges for temperature, relative humidity and carbon dioxide in the two weeks prior to the intervention, and the two weeks during the intervention.

4. If you get an alert to your phone …

- We recommend that if you get a carbon dioxide (CO_2) or humidity alert on your phone **open windows or doors for 10-20 minutes,** if you can. If it's possible, open windows wide and do so on opposite sides of the room.
- If you get an alert to heat your room, you may wish to heat the room.

Thank you for participating in our study! We will be in touch in about two weeks to collect the sensor. We will also call to ask you about your experience of having the sensor in your house.

If you are interested in learning about other ways to reduce moisture and condensation in your home, please check out the advice below.

General tips on ventilation and reducing moisture in your home

Air your home by opening windows and doors to the outside regularly. Many people find it most convenient to do this first thing in the morning. Open all the windows and doors for 10 to 20 minutes to help to get rid of some of the moisture that has accumulated overnight. A full refresh of the air in the house works better than leaving a window open all day. Ventilate even if it is raining.

Other ways to try and reduce moisture in your home include:

- Dry washing outside. If it's raining, use a washing line or rack under a covered veranda, garage or carport, or use a clothes dryer that vents to the outside, if this is possible.
- Turn on the bathroom fan before a shower or bath. Shut the door and open the window. Afterwards, leave the fan running and the windows open until the moisture clears.
- Use lids on pots when you cook. This helps to stop the steam escaping.
- Turn on rangehoods when cooking.
- Move furniture away from exterior walls in winter. A 10cm gap will discourage mould growth.
- Leave wardrobes slightly open. A little air circulation discourages mould from growing on fabric.
- Do not use unflued gas heaters – they produce a lot of moisture and poisonous gases.
- If you have a dehumidifier, you can use it on damp days. This will help to reduce condensation but it won't solve a dampness problem. It's better to tackle the sources of damp and heat alongside ventilating your home.

Picture 3: Information on how to respond to alerts and the advice sheet given to participants alongside the air quality monitor

Data collection and analysis for the follow-up interviews followed the same process as the other interviews (see section C, Study 3). While every effort was made to contact all 20 of those who participated in the monitor intervention, only 17 people could be contacted and agreed to a follow-up interview. This included 11 people interviewed as part of Study 2. The interviews took place over the phone and lasted between 10 and 30 minutes. All participants in the monitor intervention, including those who were interviewed, were provided with a $50 supermarket voucher as thanks for their time.

Ethical approval was received from The University of Otago Human Ethics Committee (application 23/026).

3 Results

Study 1: What factors of ventilation change mould levels in bedrooms?

Participant and housing characteristics from the HOME study have been described previously (Shorter et al. 2018) and are summarised in Table 1. The mean occupancy was 4.2 people per household for cases and 4.1 for control children, and houses were built on average in 1959 for case children, compared to 1960 for control children (Table 1). A high level of home ownership was seen for both cases and control households compared to the levels in New Zealand in general (81.2% and 85.7% as compared to 2013 NZ census level of 64.8% of households).

Table 1: Characteristics of HOME study participants and their homes.

Variable	Case (wheezing) n=150	Control (non-wheezing) n=300
Median age at first visit	32 months	33 months
Home ownership	81.2%	85.7%
Home occupancy	4.2 people	4.1 people
Bedroom sharing	18.2%	19.5%
Household income before tax (NZ$) median	$80,000 – 100,000	$80,000 – 100,000
House condition – self reported		
- Excellent	12.1%	18.9%
- Good	47.5%	43.4%
- Average	36.2%	34.9%
- Poor	3.5%	2.1%
- Very Poor	0.7%	0.7%
Roof Insulation (average thickness x cover)	96.6 mm	97.5mm
Average House age (QV)	1959.4	1960.1

Focusing specifically on the children's bedrooms, the number of openable windows as assessed by the building inspector ranged from 0 to 20, with a median number of 2 (Figure 2).

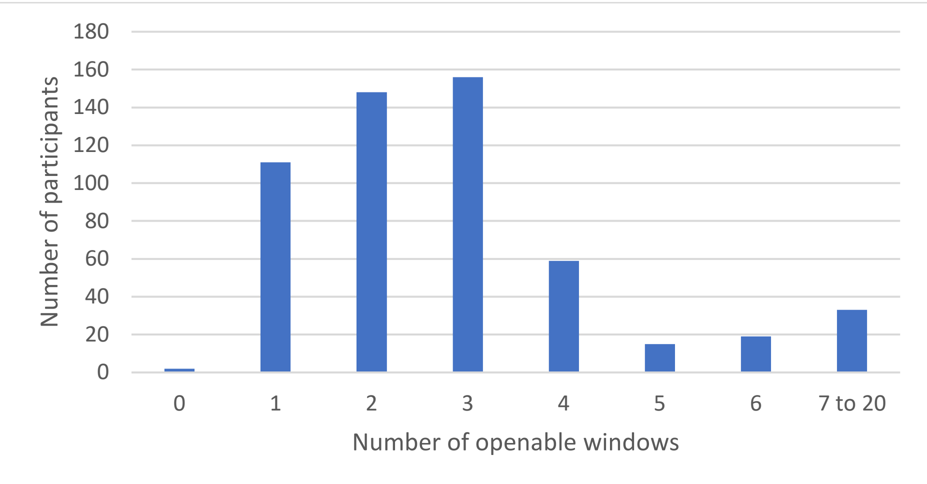
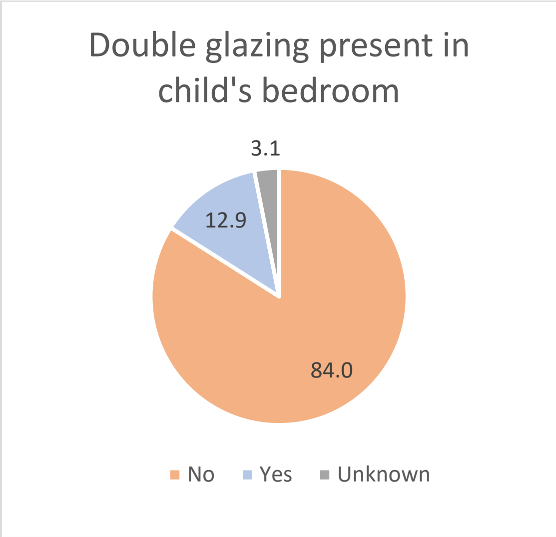


Figure 2: Building Assessor reported number of openable windows in the child's bedroom (HOME study).

Double glazing was uncommon, present in just 13% of bedrooms (Figure 3). In-home ventilation systems were reported by parents to be present in just under a third of the houses (Figure 3). Parents reported that these ventilation systems mainly comprised of those which used positive pressure to circulate air from inside the home and replace it with filtered air from the roof space of the home.



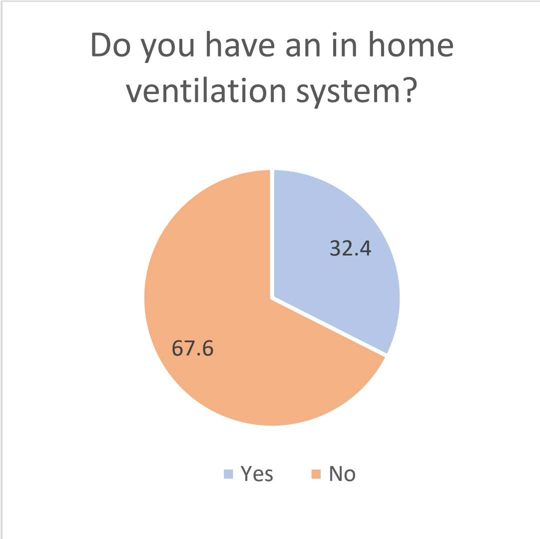


Figure 3: Percentage of bedrooms with double glazing (reported by building assessor) or self reported presence of an in-home ventilation system

Behaviours – HOME study

Households reported drying wet clothing using several methods, with outside washing lines used most frequently (95%) and inside drying racks being the next most frequent (79%, Figure 4). While clothes driers were also frequently used, many were either external to the house, or were vented. However, 98 households (22%) reported using an unvented drier within the house.

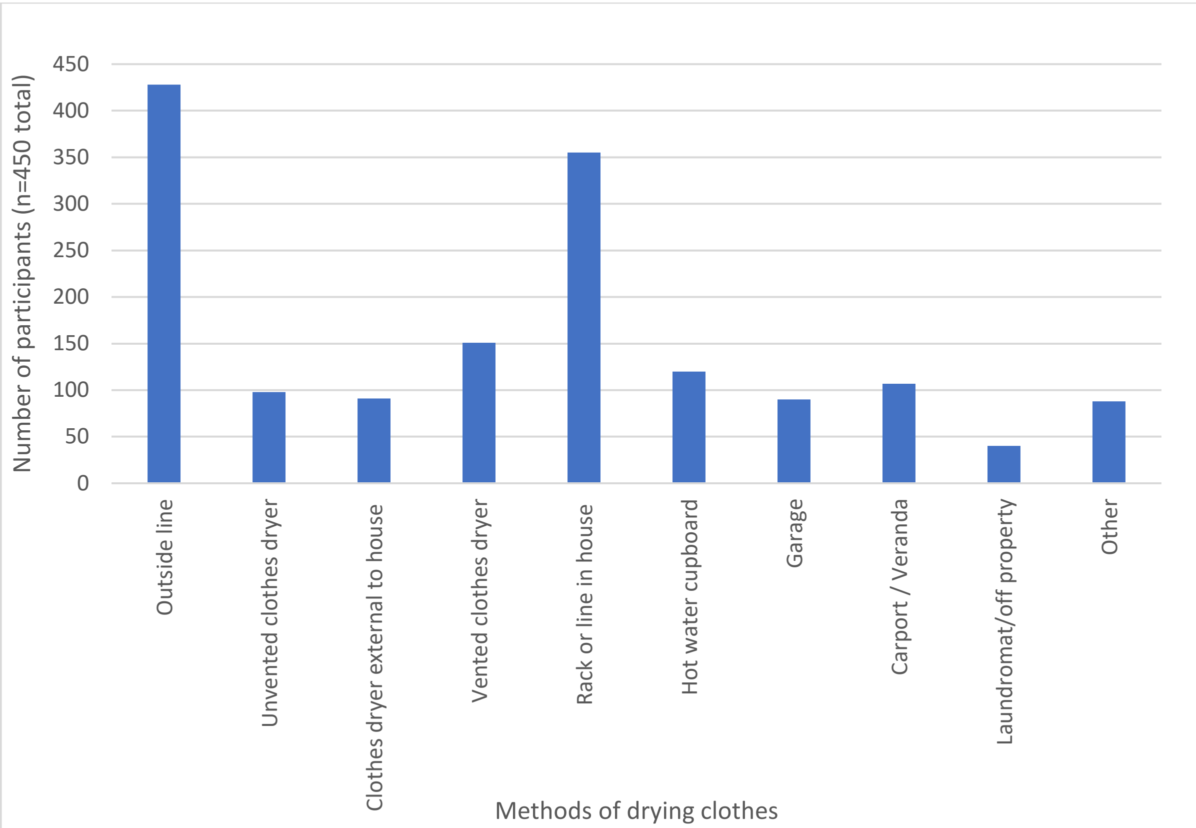


Figure 4: Self-reported methods used to dry clothes in the previous 12 months (HOME Study)

A quarter of participants reported ventilating children's bedrooms daily during winter by opening a window or door to the outside, with 38% of occupants reporting they ventilated bedrooms monthly or less during winter (Figure 5).

In contrast, children's bedrooms were ventilated much more frequently during summer by opening a door or a window (Figure 5), with 70% reporting daily ventilation, and just 8% ventilating bedrooms monthly or less during summer, suggesting that ventilation behaviour is influenced by outdoor temperatures.

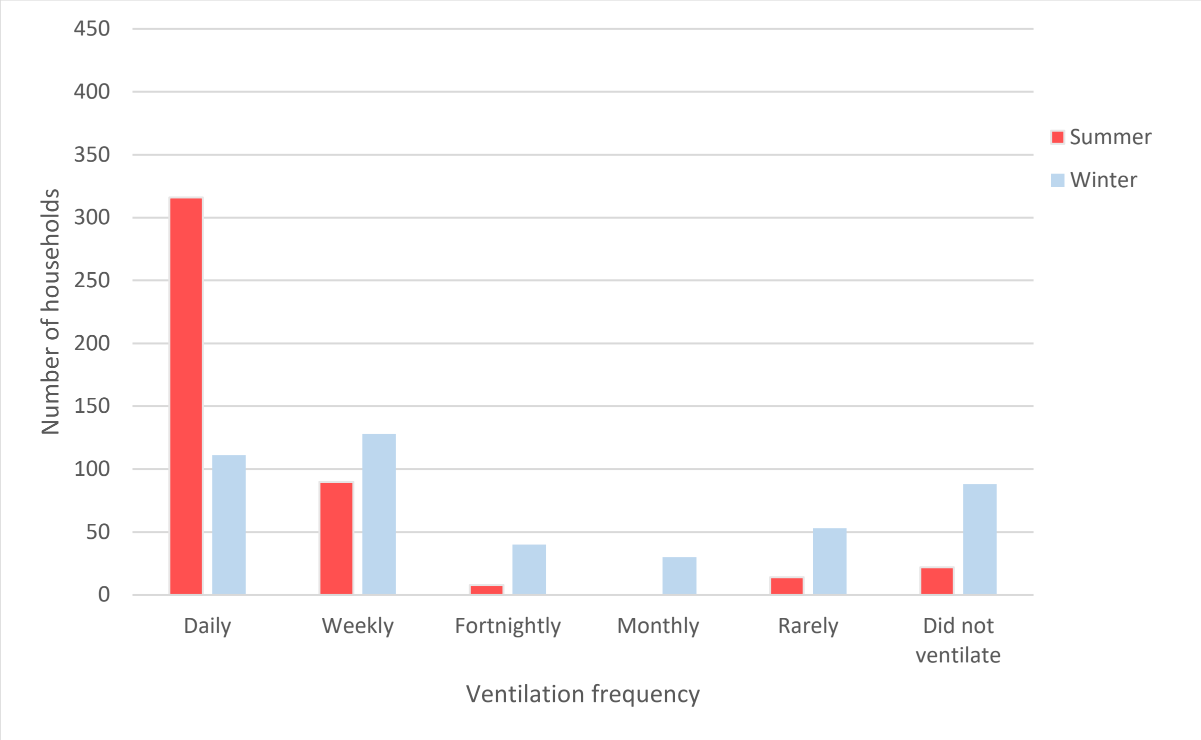


Figure 5: Reported frequency of bedroom ventilation during summer and winter (HOME study)

A similar seasonal pattern was observed for ventilation behaviour in living room areas, with 21% of households reporting ventilation of living rooms daily in winter, compared to 86% who ventilated daily during summer (Figure 6).

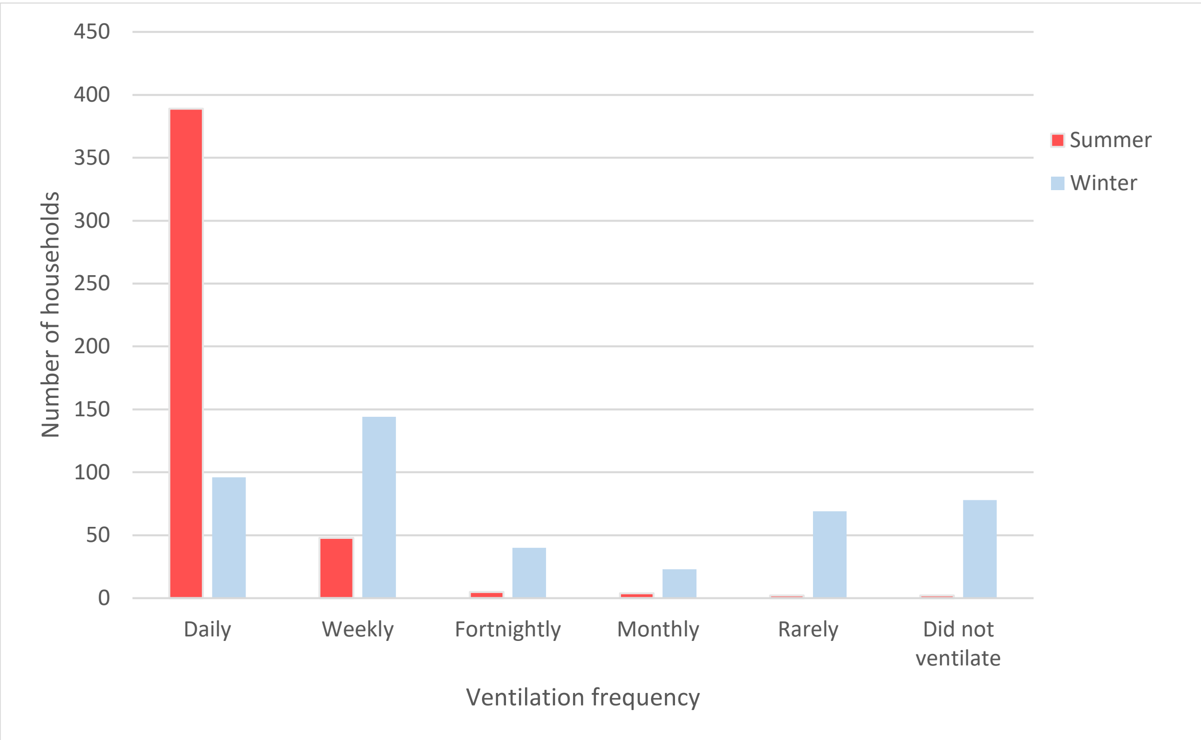


Figure 6: Reported frequency of living room ventilation during summer and winter (HOME study)

Having some form of ventilation available in bathrooms was common, with only 18.4% of households reporting having no bathroom windows that opened and 21.6% reporting not having an extractor fan (Figure 7).

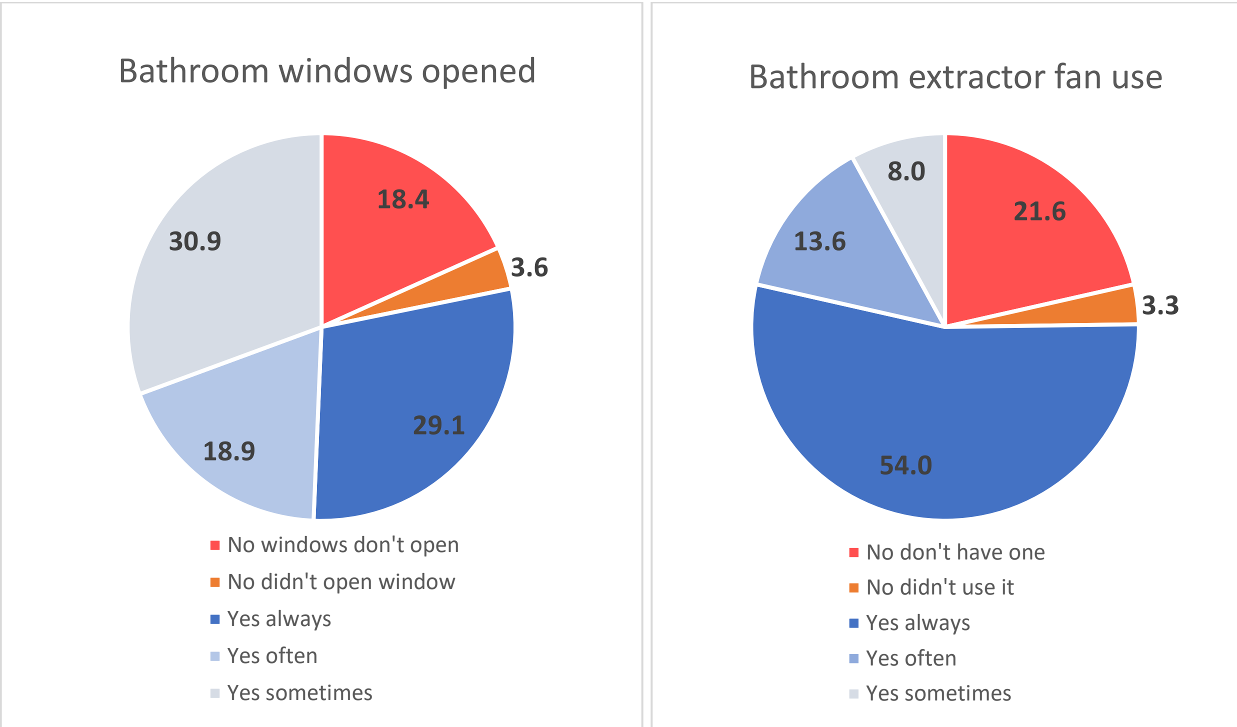


Figure 7: Bathroom window and bathroom extractor fan reported frequency of use during showering/bathing in the previous 12 months (HOME study)

Just 14 households (3%) had neither a bathroom window that opened, nor an extractor fan, making bathroom ventilation possible in 97% of households. Households who reported never using any type of bathroom ventilation, despite having them, were rare (3%), as were those reporting only sometimes using either a fan and/or an open window (10%). In total 69% of households reported always using some form of ventilation during bathing or showering activities. Over half (54%) of all households always used their extractor fans during bathing activities, with a further 14% reporting often using them. Always opening a bathroom window was less common (29.1%) than extractor fan use, however nearly half of households reporting often or sometimes opening them.

Exploring the data further, 253 households (56%) had both an extractor fan and a window available, with 99 households (22%) having only a window, and 84 households having only an extractor fan (19%). Of those with both a window and an extractor fan, 63 households were 'super ventilators' reporting always using both a bathroom extractor fan and an open window to ventilate during bathing and showering activities when they had these available (25% of those who had both available). When households had the choice to use either a window or an extractor fan, extractor fans were the more popular to use, with 72% of these households reporting always using an extractor fan, compared to 32% always opening a window, when both options were available.

Equal numbers of participants had either only a kitchen extractor fan, or only a kitchen window present to ventilate (28%), with both forms of ventilation present in 39% of households, and neither present in 5% of households. Extractor fans were frequently used during cooking activities when they were present, with 40.4% of participants reported using them always (Figure 8). Kitchen windows were often present in households, but were less frequently opened during cooking, with just 14.7% of participants reporting always opening them.

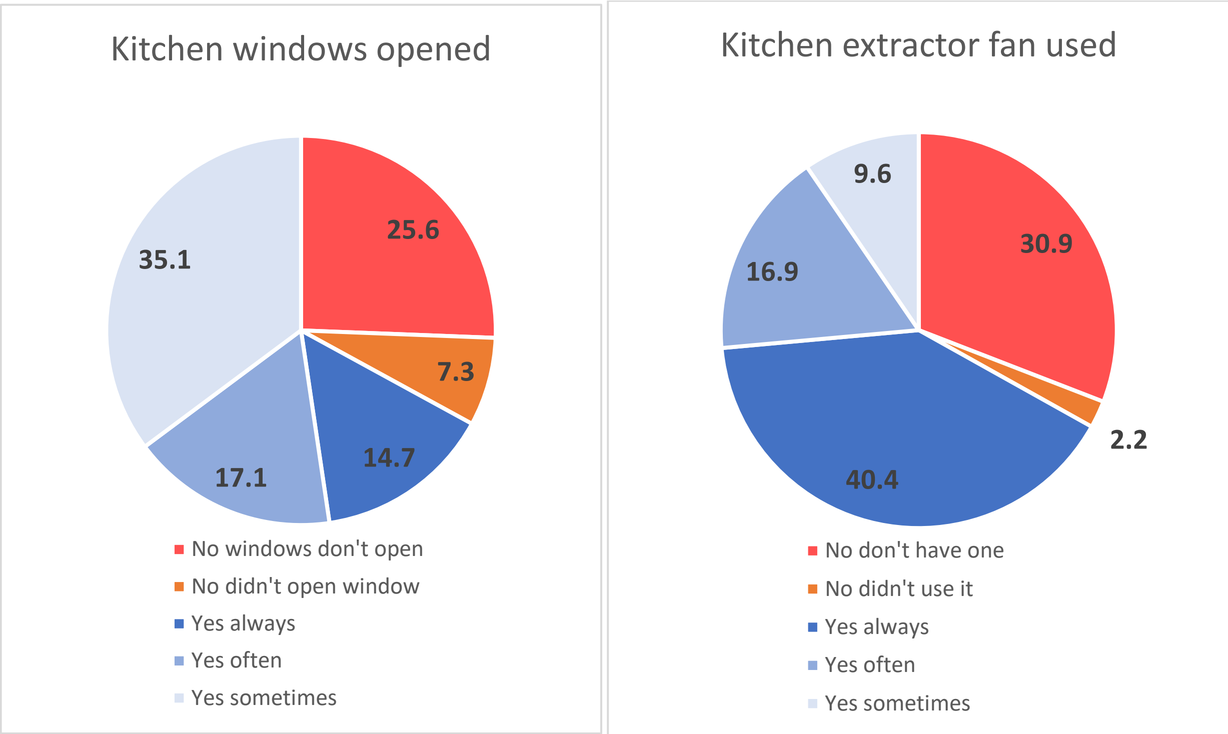


Figure 8: Kitchen window and kitchen extractor fan reported frequency of use during cooking activities in the previous 12 months (HOME study)

When both forms of ventilation were present in a kitchen, fans were more frequently used, with 63% always using an extractor fan, and just 17% always using an open window during cooking activities. There were less 'super ventilators' observed in kitchens than bathrooms (those who always used both a window and an extractor fan), with 13% reporting always using both in kitchens compared to 25%.

Factors effecting mould levels, mean relative humidity & mean temperature in children's bedrooms

Researchers observed visible mould frequently in children's bedrooms, as reported previously (Shorter et al. 2018), with 58% of the control children and 71% of the wheezing children having mould present in some area of their bedrooms. The vast majority of the observed mould was present on or around windows/windowsills and framing, followed by curtains, ceilings, walls, bedding, other areas (including flooring, doors etc) and wardrobes (Figure 9). As previously reported (Shorter et al. 2018), researcher observed mould score was significantly higher in the bedrooms of new-onset wheezing (case) children than those who did not wheeze (control children) (Figure 10).

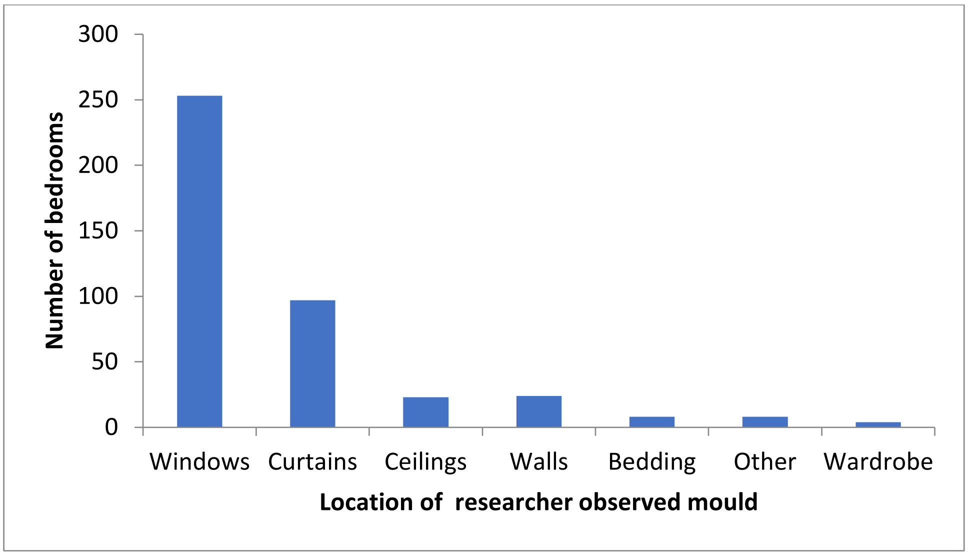


Figure 9: Locations mould was observed in children's bedrooms (from Shorter 2013)

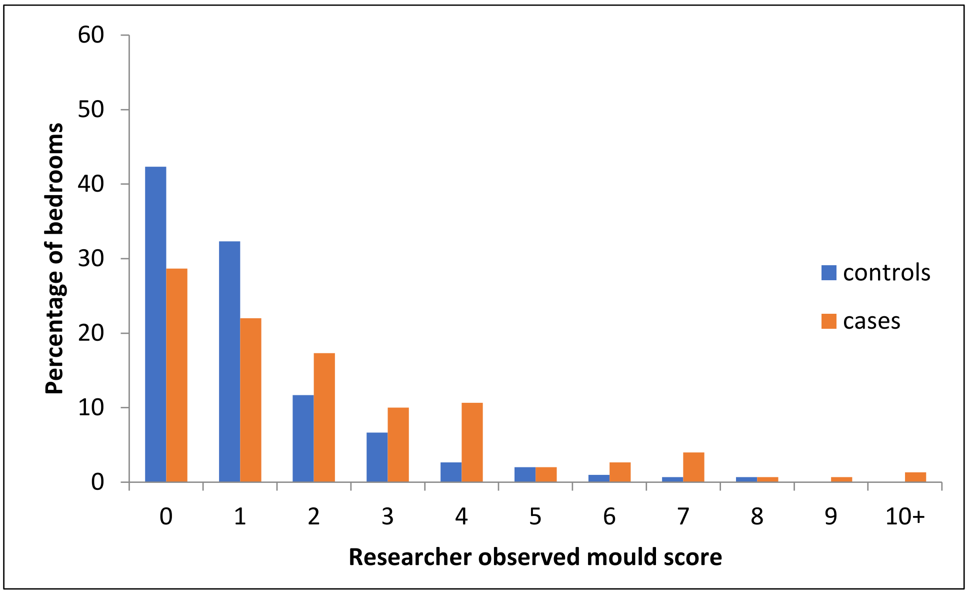


Figure 10: Mould score observations in children's bedrooms (from Shorter 2013)

Frequency of ventilation in a child's bedroom was associated with the odds of a unit increase in mould score in a monotonic fashion (Figure 11, Halley et al. 2024). Daily ventilation was associated with significantly less visible mould than ventilating monthly or less often (Monthly+), (OR 0.52, 95% CI 0.29 – 0.93, p=0.03), but weekly or fortnightly ventilation patterns did not reach significance.

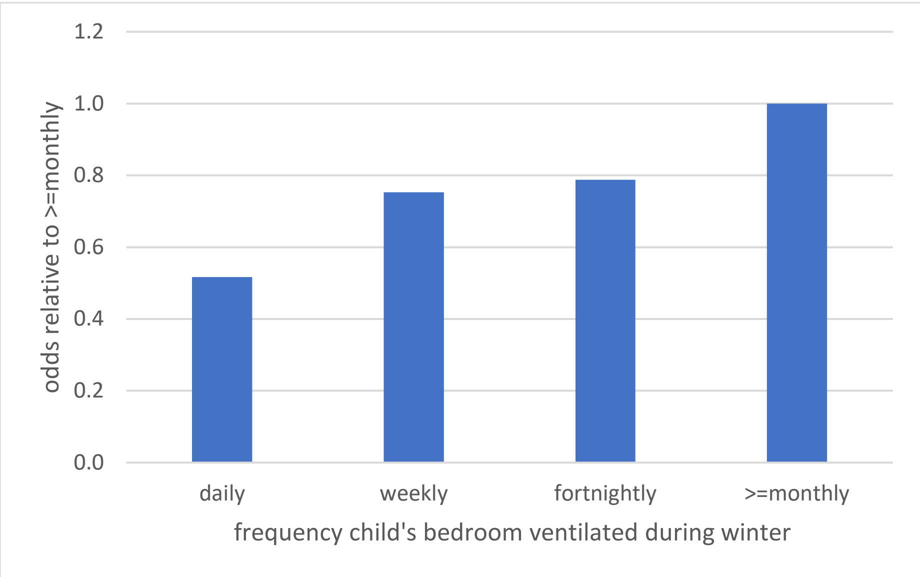


Figure 11: Relative odds of increase in mould score by ventilation frequency (from Table 2).

Examining the occupant variables that contributed to a unit increase in mould scores in children's bedrooms demonstrated that some variables were more important than others (Table 2). Also shown are the adjusted associates with levels of mean humidity and temperature with behavioural and housing characteristics.

Table 2: Adjusted associations between odds of an unit increase in mould score, adjusted associations with levels of mean humidity and temperature with behavioural and housing characteristics, with 95% CIs and p values, p≤0.05 in italics.

Variable	Odds of unit increase in mould score	Mean humidity in bedroom (% RH)	Mean temperature in bedroom (˚C)
Ventilation bedroom			
- Daily	*0.49 (0.27, 0.89) p=0.02*	*-2.77 (-4.98, -0.57) p=0.014*	*0.77 (0.18, 1.37) p=0.011*
- Weekly	0.74 (0.35, 1.58) p=0.439	-1.83 (-4.73, 1.08) p=0.218	0.13 (-0.65, 0.92) p=0.744
- Fortnightly	0.77 (0.42, 1.41) p=0.395	-0.59 (-3.08, 1.9) p=0.641	0.19 (-0.48, 0.87) p=0.575
- Never/hardly ever	Ref	Ref	Ref
Ventilation bathroom always/often	1.05 (0.62, 1.78) p=0.843	1.4 (-0.73, 3.52) p=0.198	-0.29 (-0.86, 0.28) p=0.322
In-home ventilation system	0.73 (0.5, 1.07) p=0.106	0.44 (-1.09, 1.96) p=0.575	*-0.44 (-0.85, -0.03) p=0.038*
Occupancy (per 1 occupant increase)	*1.26 (1.07, 1.48) p=0.006*	0.15 (-0.5, 0.8) p=0.657	0 (-0.17, 0.18) p=0.97
Own home	*0.47 (0.29, 0.78) p=0.003*	-0.99 (-3.02, 1.05) p=0.343	-0.16 (-0.71, 0.39) p=0.56
Case	*2.27 (1.55, 3.33) p<.0001*	-0.27 (-1.78, 1.25) p=0.731	0.18 (-0.23, 0.59) p=0.392
Control	Ref	Ref	Ref
Sun score (per 1 unit increase)	*0.8 (0.71, 0.9) p=0*	*-0.93 (-1.4, -0.45) p=0*	*0.19 (0.06, 0.32) p=0.004*
House construction			
-1920s	0.7 (0.34, 1.41) p=0.317	*3.55 (0.76, 6.34) p=0.013*	-0.35 (-1.1, 0.41) p=0.367
1921-1949	1.35 (0.76, 2.39) p=0.31	2.14 (-0.1, 4.37) p=0.062	-0.23 (-0.83, 0.38) p=0.46
1950-1979	*1.71 (1.05, 2.77) p=0.03*	2.77 (0.86, 4.68) p=0.005	-0.37 (-0.89, 0.15) p=0.16
1980-	Ref	Ref	Ref
Double glazing	*0.25 (0.14, 0.47) p<.0001*	-1.11 (-3.28, 1.05) p=0.312	0.3 (-0.28, 0.89) p=0.31
Heat child's bedroom	0.66 (0.43, 1.01) p=0.058	*-2.73 (-4.09, -1.37) p<.0001*	*0.61 (0.24, 0.98) p=0.001*

Compared to rental dwellings the adjusted odds of a unit increase in mould score was less than half in owner-occupied homes (odds ratio 0.47 95%CI 0.29, 0.78). For each additional occupant in the home the odds of a unit increase in mould score was 1.26 (95%CI 1.08-1.50). Compared to homes built after 1980 homes built between 1950 to 1979 had 70% higher odds of unit increase in mould score (OR 1.71, 95% CI 1.05 – 2.77), however older homes built prior to 1950 were not associated with a higher mould score than those built after 1980. Double glazing in the child's bedroom reduced the odds of having a higher mould score compared to singly glazing by 73% (OR 0.25, 95% CI 0.14 – 0.47). Parental reports of having sun present in children's bedrooms during winter reduced mould score by 20% for each of the five-point scale category (from sun all day, sun most of the day, sun part of the day, rarely gets sun, to no sun). There was no significant effect of ventilating bathrooms always or often on mould score in the child's bedroom compared to ventilating bathrooms less frequently, and also no significant effect of having an in-home ventilation system on mould score in the child's bedroom, compared to those who without an in-home ventilation system. There was a close to significant association between heating the child's bedroom and lower odds for increased mould score (p=0.056).

Ventilating children's bedrooms daily was associated with significantly lower mean relative humidity (2.77 %RH), and higher temperatures (+0.77 °C) in the child's bedroom when compared to ventilating bedrooms monthly or less (Table 2). Ventilating bathrooms always or often was not associated with any significant changes in mean relative humidity or mean temperatures in the child's bedroom. Other factors that were not significantly associated with either mean humidity or mean temperature in the child's bedroom included home ownership, occupancy level of the home, case status, double glazing (Table 2). Having an in-home ventilation system was associated with a significantly lower mean bedroom temperature (-0.44℃, 95% CI -0.85℃, -0.03℃), and had no association with mean relative humidity in the child's bedroom. Having a house aged older than 1920 was associated with a significantly higher mean relative humidity in the child's bedroom (3.55% RH, CI 0.76% RH, 6.34% RH) than a house built in 1980 or newer. However no other house age associations were seen for mean temperature or mean humidity. Sun score in winter was again found to be important, associated with significantly lower mean relative humidity (-0.93 % RH per one unit increase in sun score*)* and higher mean temperature in the child's bedroom (0.19℃ per one unit increase in sun score, Table 2). Parental reports of heating the child's bedroom during winter were unsurprisingly associated with an increase in both the mean temperature and a decrease in mean relative humidity in the bedroom (Table 2).

Study 2: Can receiving heating and best practice advice reduce mould levels in children's bedrooms?

As reported previously (Shorter et al. 2022) the study population had a higher level of home ownership and a higher median household income than the New Zealand population (Table 3), and a mean overnight temperature of 20℃ (range 17-23℃) was achieved in the heating intervention group, with an average heating period of 12.2 hours per night.

Table 3: Characteristics of households and participants in the Heating intervention study

Variable	
Median age of child at first visit	3 years 11 months
Gender	57% male
Home ownership	82%
Home occupancy (average people)	4.2 people
Bedroom sharing	41%
Median household income before tax (NZ$)	$80,000-100,000
Heated child's bedroom in the reported baseline winter	79%

A mean mould score of 1.61 was observed in the children's bedrooms in the intervention group on the first researcher visit, but was lower, with a mean level of 1.38 on the second researcher visit eight weeks later. A mean mould score in the children's bedrooms in the control group, who did not receive heating or advice, was initially 2.07 on the first visit by researchers, but had fallen to 1.64 by the second researcher visit eight weeks later. There was no mould present in 23% of bedrooms in the intervention group and 15% of bedrooms in the control group, suggesting advice on mould removal would have had limited impact in these households (Figure 12). Of the remaining bedrooms which did have mould present, no change in mould score was detected between the two visits in 24% of bedrooms in the intervention group and 22% of bedrooms in the control groups. Mould score increased in a similar number of bedrooms in both groups (21% intervention group, 22% in control group). A decrease in mould score was observed in 41% of control bedrooms, but only 32% of intervention bedrooms. Giving written advice on ventilation and mould removal, alongside provision of heating was not associated with a significant reduction in visible mould levels in children's bedrooms after an eight-week period (odds ratio of reduction 0.69 for intervention vs. controls, 95% CI 0.43 – 1.1).

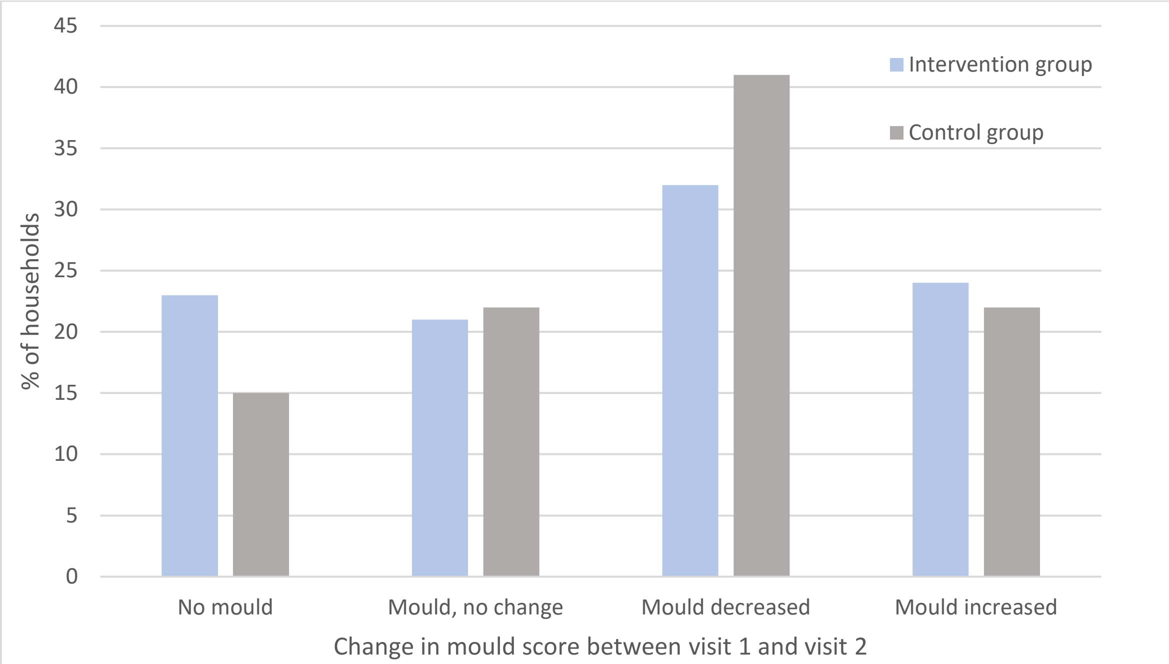


Figure 12: Change in researcher observed mould score in child's bedroom in the eight-week study period

Study 3: What are peoples ventilation practices, beliefs, and barriers?

The key themes arising from the interviews with housing assessors and people living in damp housing were as follows. First, years of experience of living in damp housing has created high levels of "damp intelligence": awareness of why the dwelling was damp and what could be done the problems caused by damp housing and of ways to minimise moisture in homes. Second, living in damp housing degrades quality of life, impacting on participant's comfort and health, and costing them time, labour and money. Third, despite their high level of damp intelligence, participants were hampered in their ability to reduce dampness because of deficiencies in the dwelling's structure or fittings, and the cost, inconvenience and labour associated with exercising some moisture-reduction strategies.

1. *Knowledge about indoor moisture*

The first significant finding was that participants possessed a great deal of knowledge about indoor moisture and, as subsequently discussed, the association between damp housing and poor health ". Participants shared their insights on how their dwelling's topographical placement, structure, and fittings affected the moisture in the home. They noted the daily routine and products they found useful in minimising moisture.

Dwelling placement and structure: Participants valued a sunny home and big windows to help reduce dampness. People often placed the blame for dampness issues on the home's position in a valley or in the shade of trees or other homes. For other participants, leaks in the building fabric were responsible. These issues were indicated by "bubbly" wallpaper, or water flowing into the house through the ceiling or leaky windows and doors in rainy days, and damp patches on walls, floors, and ceilings.

Fittings and products: Participants valued extractor fans and heat pumps – both on the heat setting and the "dry" setting to reduce dampness. Several noted that shower domes or a heat recovery ventilation system helped or would help reduce the dampness in their home. Participants used products to help them manage the moisture issues in the home: "squeegees", "scoopees" or window vacuum cleaners to remove condensation; dehumidifiers; heaters, and moisture absorbers such as damp rid. Some participants had a hygrometer which displayed information about the relative humidity level in the room. Some participants reported using these to decide when to open or close windows, or whether it was a good day to dry laundry inside (i.e. if the relative humidity was low).

Daily routines. People reported their daily routines regarding managing moisture. For some people, the day began by scooping or soaking up the condensation in the windows; others simply opened windows to help address the condensation. People were knowledgeable about the importance of opening windows and using extractor fans, especially when cooking and bathing and for half an hour or so after cooking and bathing, as well as keeping pot lids on and avoiding hanging laundry inside. Some participants habitually kept at least some windows open all the time, especially the bathroom window. Other participants ventilated once or twice a day by opening all the windows or enough to create a through-draught, before shutting them again after about half an hour. There was a large range of heating behaviour, from those who used heating constantly, to those who never heated.

Learning: In most cases, people reported that they had learned about how to reduce moisture in the home as children. People described childhoods where windows were open most of the day. They had also learned from trial and error and living in different homes and with different people. Participants referred by Sustainability Trust and K'aute Pasifika reported that their housing assessor had been helpful in educating them about the importance of ventilation, in particular, in changing the habit of keeping windows always open (or always closed) to opening all the windows for half an hour or so before closing them, in order to allow the house to heat up.

Interviews with assessors and people living in damp housing had much in common regarding the sources of moisture in homes, and ways of managing moisture. One important difference was that just mentioned: whereas assessors advocated thorough ventilation followed by closing up and heating, many people living in damp housing believed that keeping some windows open all the time or for a good proportion of the day would reduce moisture most effectively. Another contrast was that people living in damp housing raised dehumidifiers, moisture absorbers, and HRV as important parts of the moisture-reduction toolkit; these tools were not prioritised by assessors.

2. *Impact of damp housing on quality of life*

Despite the high level of knowledge about how to manage dampness, and, likely, living in less damp condition than they might otherwise have thanks to that knowledge, participants continued to live in damp housing. This had a number of impacts on their lives.

Discomfort and inconvenience: People described rotten floors, patches of mould on the walls, curtains and belongings, wet walls, carpet "squelchy" with moisture. They described belongings infested by mould and drawers not opening due to the wood swelling from moisture. They described damp sheets on their beds, taking clothes out of wardrobes to find them heavy with moisture, and towels never drying before it was time for the next day's shower. The conditions of the home caused them to avoid going home, or to minimise time in certain rooms. One participant reported keeping the toilet door closed at all times, and ensuring her children did not stay long in there, due to her fear of them being exposed to the mould there.

Mental and physical health: Damp conditions harmed health. In the case of those participants referred by the Sustainability Trust, their children had been hospitalised for health conditions related to housing. Other participants described the onset or worsening of asthma and other respiratory conditions, and a condition a participant described as "mould poisoning". Other people described feeling sad, angry and depressed as a result of living in a damp home. One participant had moved from a very damp home to a less damp home, five months prior to the interview. She said that her mental health had improved a lot, and she had attended class and socialised much more often. In other cases, participants said that it was hard to tell if their health had been affected by living in damp and mouldy housing, given damp housing was all they had experienced.

Labour and time: The damp housing conditions created work for participants. Implementing the daily routines mentioned above – removing condensation, opening and closing windows, wiping down bathrooms, emptying dehumidifiers – all took time and effort. This was especially the case for the worst housing. One person reporting scooping up a litre of water from her bedroom windows every morning; another reported emptying the dehumidifier multiple times a day. Opening all the windows and doors in the house, and closing them all, took a lot of time, and was difficult to coordinate for busy people on their way to work and/or to drop children off. Another time-consuming activity was removing mould. Participants reported that removing mould was a tedious, uncomfortable and exhausting task. Some participants removed mould ever few days, while for others this was a monthly activity or occurred a couple of times a year.

Cost: There were many costs associated with living in damp housing. People reported purchasing window vacuum cleaners, disposable moisture absorbers such as Damp Rid, and dehumidifiers to attempt to reduce the moisture. For example, participants (including people who suffered health issues such as asthma) described homes where they had to run the dehumidifier constantly in an attempt to control moisture. They also lost money by mould and moisture destroying belongings including a bookcase, a handbag, computer game case, and clothes and shoes. More broadly, there were significant costs to mental and physical health, as already discussed.

3. *Impediments to reducing dampness in housing*

There were a number of impediments to reducing dampness in housing. One salient one was the lack of well-functioning extractor fans in the bathroom or kitchen. Participants reported that some extractor fans were blocked or were so weak they did not remove much moisture; one participant avoided using a fan because it vented to the ceiling. These participants reported that their landlord was unwilling to address the situation or that they preferred not to report the issue to the landlord. Some extractor fans were too loud. One participant said she felt uncomfortable using the kitchen fan for long periods because she could not hear her children if they needed her; for others, the noise interfered with conversation, watching tv, or could disturb flatmates' sleep. In some cases, the extractor fan in the bathroom was built into the light-switch. This made some people more likely to use the extractor fan; however, in one case, it reduced use of the fan as the participant did not want the light on at night.

Participants reported a number of barriers to opening windows as frequently as they might. Some people were concerned about neighbourhood noise, outdoor air pollution, or bugs or birds entering the home. Others reported windows needed to be shut for safety or to keep pets inside. People reported that their windows are jammed because of water swelling the wood, or broken entirely, which means they cannot be opened wide, or properly closed. Finally, people avoided opening windows when it was raining or very windy.

Participants were unable to clean mould as often as might be necessary due to the aforementioned time, labour and discomfort associated with the task. This was particularly the case for people with existing health conditions, and those who felt that exposure to mould in the cleaning process further harmed their health. In some cases, mould was on very high ceilings which was difficult or unsafe to access.

Heating, as noted in the interviews with assessors, is important to reducing moisture and discouraging mould growth in housing. A number of occupants, and particularly those with children, were committed to heating the home because of its importance to health. However, others only heated minimally because of the expense. For example, one participant said that the flatmates had agreed only to use the heat pump if more than two people were going to be spending time in the lounge. These participants elected to use hot water bottles, extra clothing, or bedding to keep warm.

As already noted, everyone was aware of how drying laundry inside contributes to dampness in homes. While some people used outdoor lines, this was often not possible due these getting little sun and taking a long time to dry in Wellington's often inclement weather. Many people avoided drying laundry inside by using dryers or laundromats. However, other people did not have dryers, had dryers that function poorly, or had dryers that vented inside, which contributed to dampness. They were unwilling to use dryers or laundromats because of the cost. Instead, they dried laundry inside. One participant reported the constant use of three drying racks in the lounge by the seven flatmates in the house; there was competition for drying rack use and laundry would never completely dry.

The interviewers with assessors raised these same issues regarding impediments to reducing moisture in the home. However, when their own clients raised these issues, they were often able to come up with strategies to address them. For example, they were able to advise on effective use of the heat-pump, and advocate to the landlord to improve the extractor fan. If people raised concerns about the safety of pets or children if windows and door were open, assessors could recommend certain windows to open that could ensure safety while still providing a reasonable through-draught. Assessors could provide information on the cost of using the dryer (less than is sometimes imagined) or come up with strategies for how to dry laundry inside while minimising moisture ingress. For example, one assessor recalled a situation where they recommended opening all the windows in a certain room where the drying rack could be placed, and the closing that room off from the rest of the house.

Study 4: Can smart monitor technology change ventilation behaviour? Pilot study

The post-intervention interviews with participants revealed that all generally approved of the monitors, with most saying they would like to purchase one or would recommend to others. Some of those who had previously used a basic hygrometer (all of whom were referred by Sustainability Trust, and had been provided with a hygrometer as part of their service), commented that they had not known what the numbers on the basic hygrometer had meant, or they had forgotten about it, in part due to lack of notifications, or it had run out of batteries. Perhaps in part because the air quality monitor was new to them, most participants were enthusiastic about the monitor.

Opinions varied about the monitor notifications on the phone. Several people said they did not use notifications and just used the monitor display. Several participants noticed that they paid less attention to the alerts as time went on and they grew accustomed to what those alerts were. One comment was that it would be good to customise notifications as to preferences: it was annoying to get many alerts about cold temperature when they were unwilling or unable to heat the home. Another opposed phone notifications in general because they prefer to minimise distractions. For others however, the notifications were key to reminding them about air quality. In some cases, participants had the settings on such that the monitor gave them alerts only when they were at home. In other cases, the monitor alerted them to problems in the air quality even when they were not at home, which was sometimes annoying. One participant felt anxious getting a notification about the $C0_2$ levels in her daughter's room, when she was at work and could do nothing to address it. In contrast, another participant was grateful to receive notifications about how cold it was at home. It motivated him to contact his partner and encourage them to heat the home.

In general, participants approved of the design of the air quality monitor. One identified issue was the inability to use the app to explore long-term trends which would enable people to see how their home performed while they were sleeping; one participant suggested a weekly report on air quality would be useful.

Most participants (n=14) said that they had changed their behaviour in response to the monitor display and notifications. A minority of the intervention participants (n=6) said that the monitor had not changed their behaviour. (This is also likely to be the case for the 3 people who participated in the intervention study that we could not contact for the follow-up interview).

Most participants (14/17) said they changed their window-opening behaviour in response to the monitor (Table 4). They sometimes or always opened windows or doors when the monitor prompted them to. One participant (Household 10) was concerned about troublingly high VOC levels, which meant that they did not pay attention to the alerts that were the focus of this study. Two participants reported that the monitor alerted them to open window when they already had windows open; they habitually had windows open all day (Household 7, 17). One participant (household 1) reported that, even with the dehumidifier on all day, and having the windows open most of the time, they could not reduce the relative humidity to a healthy level.

Table 4: Self-reported behaviour change in response to monitor

Household	Sometimes or always opened windows in response to monitor alerts	Sometimes or always heated the room in response to monitor alerts
1	Yes	No
2	Yes	Yes
3	Yes	Yes
4	*Not interviewed*	*Not interviewed*
5	Yes	Yes
6	*Not interviewed*	*Not interviewed*
7	N/A (windows already open)	No
8	*Not interviewed*	*Not interviewed*
9	Yes	N/A (did not recall getting alerts)
10	No	No
11	Yes	N/A (did not recall getting alerts)
12	Yes	No
13	Yes	Yes
14	Yes	No
15	Yes	No
16	Yes	Yes
17	N/A (windows already open)	No
18	Yes	No
19	Yes	Yes
20	Yes	No

Six participants said they heated the home more than they normally would because of the monitor's readings during the intervention period. Three commented that the monitor made them realise they were cold, when sometimes they had not noticed (Household 3, 5, 13). One reported that, in response to the information sheet, he had changed his habit from keeping windows open all day, to opening them for a short period and shutting them again (Household 3). Four people who did not follow monitor alerts regarding temperature said that this was because they could not afford to; they said they preferred to put on more clothes, use a hot water bottle, or spend time in another room (Household 1, 7, 17, 18). One participant did not heat in response to the alerts because they were confident the room was warm enough for their children, given their warm bedding (Household 10). Other people sometimes did not follow monitor alerts regarding temperature because they were not cold (Household 19, 20). Some participants noted that it was difficult to manage getting the balance of C02 and temperature correct.

One household had an issue with the VOC sensor. The monitor was examined against a second monitor and appeared to be exhibiting an upwards drift. This resulted in a number of alerts to the occupant, which the occupant found distressing. This is a reminder that any air quality monitoring equipment used in trials must be accurate, and the information that the monitor provides must be understandable to the occupant.

It is important to note that the value of having the monitor besides behaviour change. For three of the participants, the monitors' readings about poor air quality were validating: it was a relief to have objective proof supporting their assessment of the dwelling (Household 1, 2, 7, 17). For two participants (Household 11, 15), the monitor's readings were reassuring: they had assumed, in one case due to children's poor health, that their home was cold and damp, and were pleased to see that it was not so bad.

Using the percentage of time spent in optimal zones proved to be an effective way to understand the conditions in the monitored room, and whether any improvement was observed. The percentage of time that the twenty households spent in the optimal temperature, relative humidity and carbon dioxide zones varied widely between households (Figure 13 – 15), from some households spending no time in the optimal zone, all the way through to some being in the zone for over 90% of the time (e.g. Temperature, Figure 13).

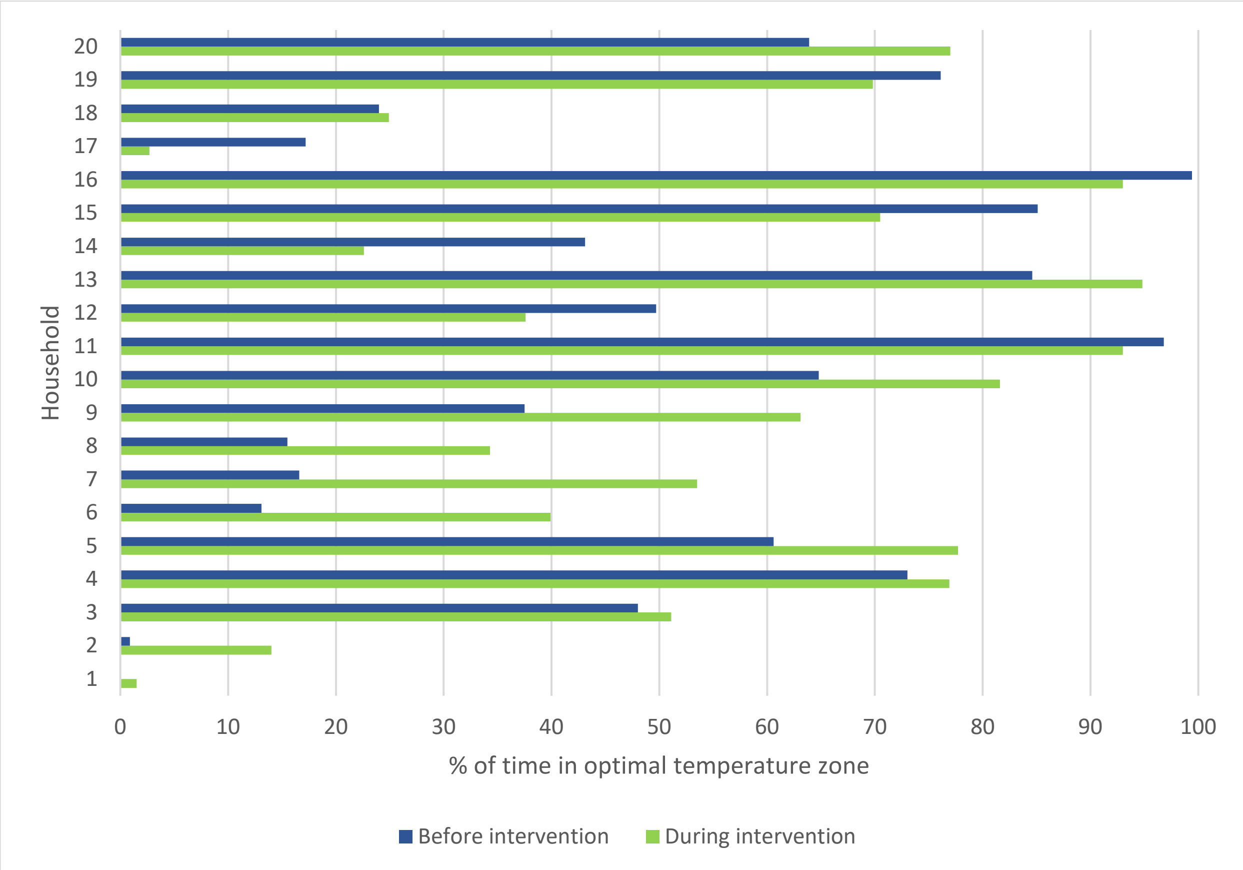


Figure 13: Percentage of time households spent in the optimal temperature zone before and during the intervention

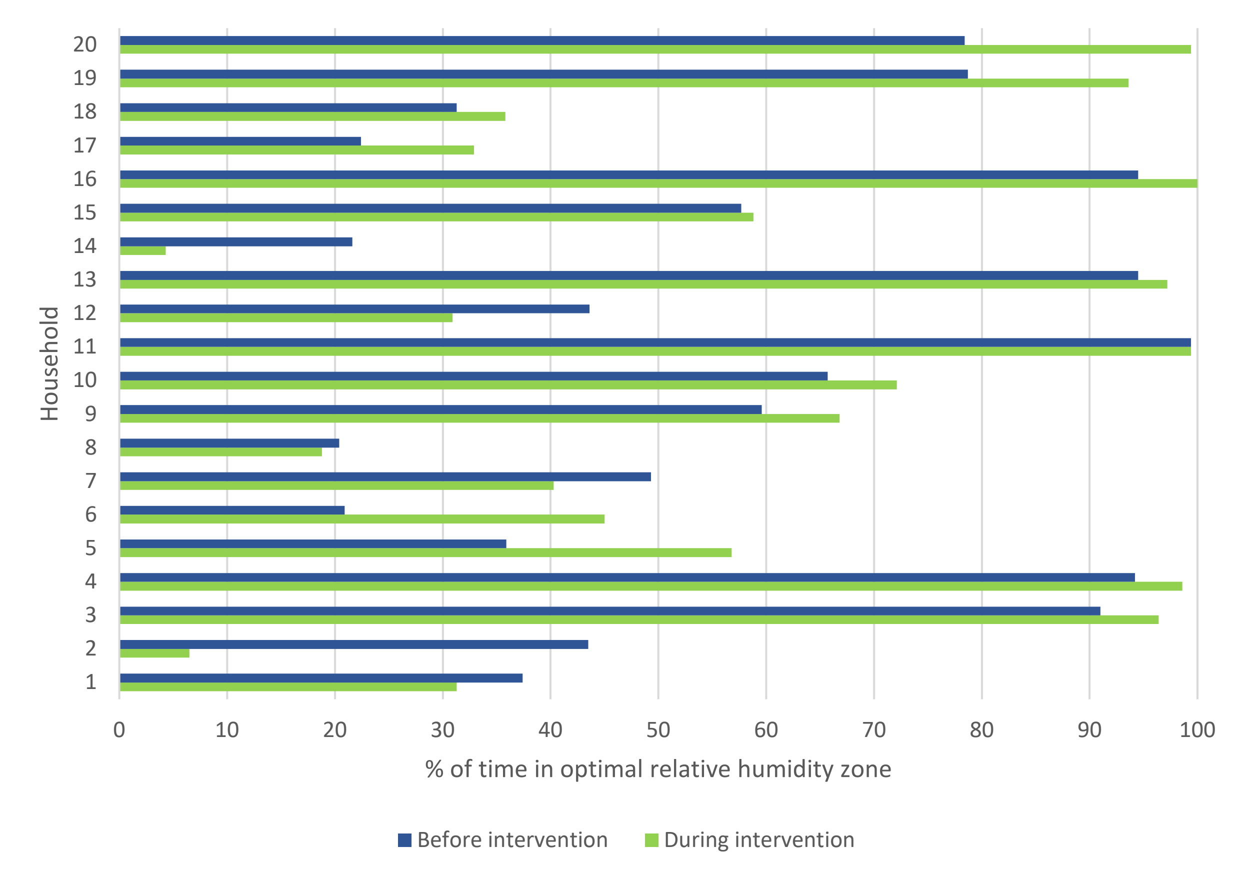


Figure 14: Percentage of time households spent in the optimal relative humidity zone before and during the intervention

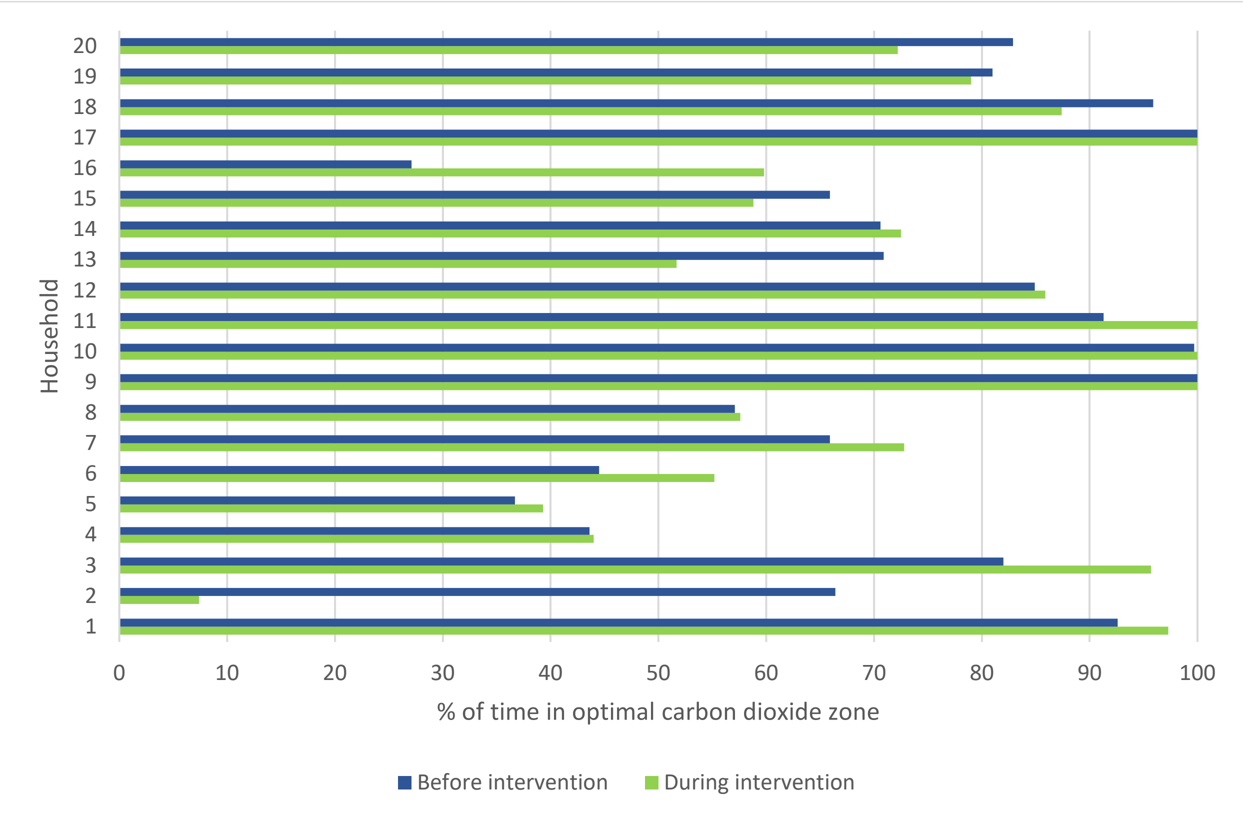


Figure 15: Percentage of time households spent in the optimal carbon dioxide zone before and during the intervention

Improvement in time spent in the optimal zones during the intervention also varied widely by household (Figures 13 – 15, improvement achieved when the green lines are longer than the corresponding blue lines). Encouragingly there were several households who saw gains, particularly with heating behaviours. Some households saw modest improvements in all measures, others saw little improvement or, in some cases, worsening conditions. These findings concur with those from the qualitative interviews, that whether conditions improved depended on the individual, in particular their housing characteristics, their engagement with the monitor and also their constraints on following the advice (e.g. high cost of heating may be prohibitive to following heating alerts). While this is a small sample, statistical t-tests were carried out and found that significant changes ($P \leq 0.05$) were not observed during the intervention compared to the period prior to the intervention for temperature, relative humidity or carbon dioxide. Carbon dioxide behaviour may not have been able to have been changed in response to the intervention because most carbon dioxide alerts would have occurred during the middle of the night, when occupants were sleeping. Having access to the data over a 24-hour period on the app, rather than just showing data from the last hour, would be of benefit to the occupants. While data are not presented here, changes in mould score between visits were not observed, and unless mould was removed due to cleaning activities, would not be expected to be reduced in such a short intervention period. Running the intervention over a longer timeframe and prior to autumn and winter mould accumulation would make this measure more relevant in future assessments.

These findings concur with those from the qualitative interviews, that whether conditions improved depended on the individual, in particular their housing characteristics, their engagement with the monitor and also their constraints on following the advice (e.g. increasing cost of heating may be prohibitive to following heating alerts). While this is a small sample, statistical t-tests were carried out and found that significant improvements were not observed during the intervention compared to the period prior to the intervention for temperature, relative humidity or carbon dioxide ($P \leq 0.05$). Carbon dioxide behaviour was not as effectively changed, and this may well be because most carbon dioxide alerts would have occurred during the middle of the night, when occupants were sleeping. Having access to the data over a 24-hour period on the app, rather than just showing data from the last hour, would be of benefit to the occupants. While data is not presented here, changes in mould score between visits were not observed, and unless mould was removed due to cleaning activities, would not be expected to reduce in such a short intervention period. Running the intervention over a longer timeframe and prior to autumn and winter mould accumulation would make this measure more important in future assessments.

D. Discussion

Study 1

This study examined mould, temperature and humidity in relation to ventilation behaviour patterns in homes, with a particular focus on the child's bedroom environment. The study demonstrated that a daily pattern of opening bedroom windows in winter was associated with a reduced amount of visible mould, when compared to rarely or never opening the windows. While it did not reach statistical significance, opening windows weekly or fortnightly also led to a reduction in mould. Alongside ventilation, winter sunshine levels appear to be particularly important in reducing mould. This may be through increased warmth with solar gain or potentially directly through UV exposure (some will be filtered out by windows, e.g. UVB, but not all of UVA), which can denature fungal spores. These findings imply that when building new houses particular thought should be given to ventilation in bedrooms and how much solar radiation a home is likely to receive during wintertime. Other factors that led to less mould included increasing the warmth in the room (nighttime heating the bedroom) or reducing condensation (double glazing, newer houses with better insulation levels), or lower house occupancy (less moisture generation via respiration, laundry, bathing and cooking activities).

Several of these factors have already been updated in the Building Code for new builds, but consideration should be given to the benefits of retrofitting older housing stock, where it is practical.

There were high reported levels of ventilation during cooking and showering/bathing activities, with mechanical ventilation favoured over window opening, and very few houses having no form of ventilation in these areas. There is still potential for improvement here though, and one potential intervention would be having fans that switch on automatically when moisture levels are high (integrated moisture monitors). Interestingly bathroom ventilation was not found to be associated with the levels of mould in the child's bedroom, suggesting localisation of mould by room, and that factors more directly associated with the bedroom environment have a greater impact on mould growth. The high level of reported clothes drying indoors is concerning and may be one area to target to reduce the accumulation of moisture in homes. However, it is likely that there may be no other affordable option currently available for some families other than to use drying racks inside during wet weather. Investigating how moisture could be minimised for these activities would be worthy of further study (e.g. such as using racks with a window partially opened, or, for future house building, providing areas to dry clothes outside that are sheltered from rain, or use of subsidised laundromat services).

There are some limitations with the study. Firstly, the geographic area studied (the Greater Wellington region) was small, and these results may therefore not be applicable to all climatic areas of New Zealand. Data was not collected on outdoor temperature, which would have been potentially useful for further analysis. Additionally, we did not gather information on length of time windows were opened, which could vary from a few minutes a day to all day. We also did not ask questions about what the barriers to ventilation might be (security concerns, shortage of time). When collecting data on use of the in-home ventilation system asking whether a vent was present in the child's bedroom would have been useful, although we note that reported presence of these in a home was associated with a lower temperature in the bedrooms, suggesting that they did have a direct impact on the bedrooms. There was a high level of home ownership in this cohort, and we know from previous studies (as well as this study) that mould levels can be higher in rented homes. Most mould was found around windows in this study, and so the results may not be applicable to homes with more extensive mould on walls, ceilings and furniture – ventilation may not improve mould levels in these homes.

Study 2

Giving written advice on ventilation and mould removal, alongside provision of heating was not associated with a significant reduction in visible mould levels in children's bedrooms after an eight-week period compared to a control group. This suggests that these activities alone may not be enough to reduce mould in a bedroom. There are several ways that this intervention could be improved. As suggested by the results in Study 1, a potential intervention that combined heating with daily ventilation may have led to lower levels of mould in the bedrooms. A longer study period could be employed as eight weeks may not have been enough time to see a reduction in mould. A longer study period could include all of autumn and winter, which could have meant seasonal mould did not have a chance to establish. Additionally, a more in-depth look at what factors were contributing to mould for each household, and then tailoring the advice separately for each household may have resulted in a better uptake of the advice. Having someone give tailored advice, rather than having a written information sheet may also be an area to explore to see if it results in better uptake. This is something that is already utilised by some community organisations, such as those that are part of the Healthy Housing Initiative, where their assessors talk directly with occupants.

Study 3

The key themes arising from the interviews with housing assessors and people living in damp housing were as follows:

First, years of experience of to damp housing created high levels of understanding about household moisture: awareness of why the dwelling was damp, what could be done to address the problems caused by damp housing, and ways to minimise moisture in homes. For the most part, the knowledge about best practices to reduce moisture in homes was consistent between assessors and for the occupants living in damp housing. One important exception however was that whereas assessors recommended opening windows wide to ventilate thoroughly once or twice as day, many of the occupants living in damp housing opened windows partially for the whole day or for a large proportion of the day. This is a potential problem because over ventilation can lead to unnecessary heat loss.

Second, living in damp housing degrades quality of life, impacting people's comfort and health, and costing occupants time, labour, and money.

Third, despite their extensive knowledge about managing moisture, occupants living in damp housing were often hampered in their ability to reduce dampness because of deficiencies in the dwelling's structure or fittings, as well as the cost, inconvenience and labour associated with exercising some of the moisture and mould-reduction strategies. Assessors reported that these issues affected their clients' ability to improve the indoor air environment as well; however, they were able to recommend workarounds and provide information based on their clients' particular situation, which could sometimes overcome those impediments.

This study shows how occupants living in damp housing have developed innovative strategies to deal with chronically damp housing; however, their home environments, in many cases, remain far from ideal. It also underlines the importance of tailored advice to people living in particularly damp housing.

Study 4

Our pilot study demonstrated that use of air quality monitors in homes is a feasible intervention. The monitors were generally well received by occupants and the units themselves were very easy to set up, had an excellent screen interface, alert levels could be readily changed, and there were no interruptions in data collection using the IoT. Participants reported they found the data useful, with most reporting that they opened the windows more or heated the room more than they would otherwise have. The sensor validating for those who had long been concerned about the cold and damp issues in the home, and who now had the data to back up their assessment. For others, it reassured them that the conditions in their home were not as bad as they had feared.

The use of percentage of time household is in optimum conditions was a useful statistic for understanding house conditions quickly. The app could be improved by showing participants a graph of the last 24 hours of data, rather than just the one hour that is currently provided. This was particularly apparent for CO_2 levels, which peaked overnight, and occupants had no way of checking for how long their levels were raised and were therefore less well informed to act. Participants found the data useful, with a number reporting that they opened the windows more or heated the room more than they would otherwise have. For those who had long been concerned about the cold and damp issues in their home, the monitor provided validation, giving access to data to confirm their assessment. For others, it reassured them that the dampness conditions in their home were not as bad as they had feared.

Limitations to the study included that the intervention was conducted in a small number of homes, for a small timeframe (two weeks), and would need to be carried out in a larger number of homes for a longer time frame to reasonably be expected to impact indoor mould levels. Habituation to alerts would need further investigation in a longer trial, although it is hoped that behavioural change may be achieved before that occurred.

Smart monitors are one potentially useful tool to alert occupants to indoor air quality issues, but the actions required to address poor indoor air quality may not be simple for occupants to take. Better training of occupants in the use of the monitors, particularly the apps and what actions to take, may result in better uptake. However, there are some barriers to their success, such as cost of heating rooms, and deficiencies in the dwelling's structure and fittings which mean that improving air quality would require actions far beyond simply heating or ventilating more. Such actions might include repairing leaks, improving insulation, fixing windows so that they open and shut easily, and improving extractor fans.

E. Conclusions

This research has demonstrated that occupant ventilation behaviour can influence the amount of mould in homes, and that ventilation is one key factor in keeping homes healthy. Our research has investigated and recommends several potential interventions that may lead to improved ventilation practices in a home. Written advice alongside heating for eight weeks in cooler seasons was not sufficient to reduce mould levels. Indoor air quality monitors may provide a helpful prompt to change ventilation behaviour, however ventilation behaviour can be complex, and be influenced by environmental and individual constraints that may make it difficult to follow best practice advice, or have that advice improve the conditions of a home. Tailored advice aimed at engaging with people's actual situations and overcoming individual impediments to ventilation may be useful.

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