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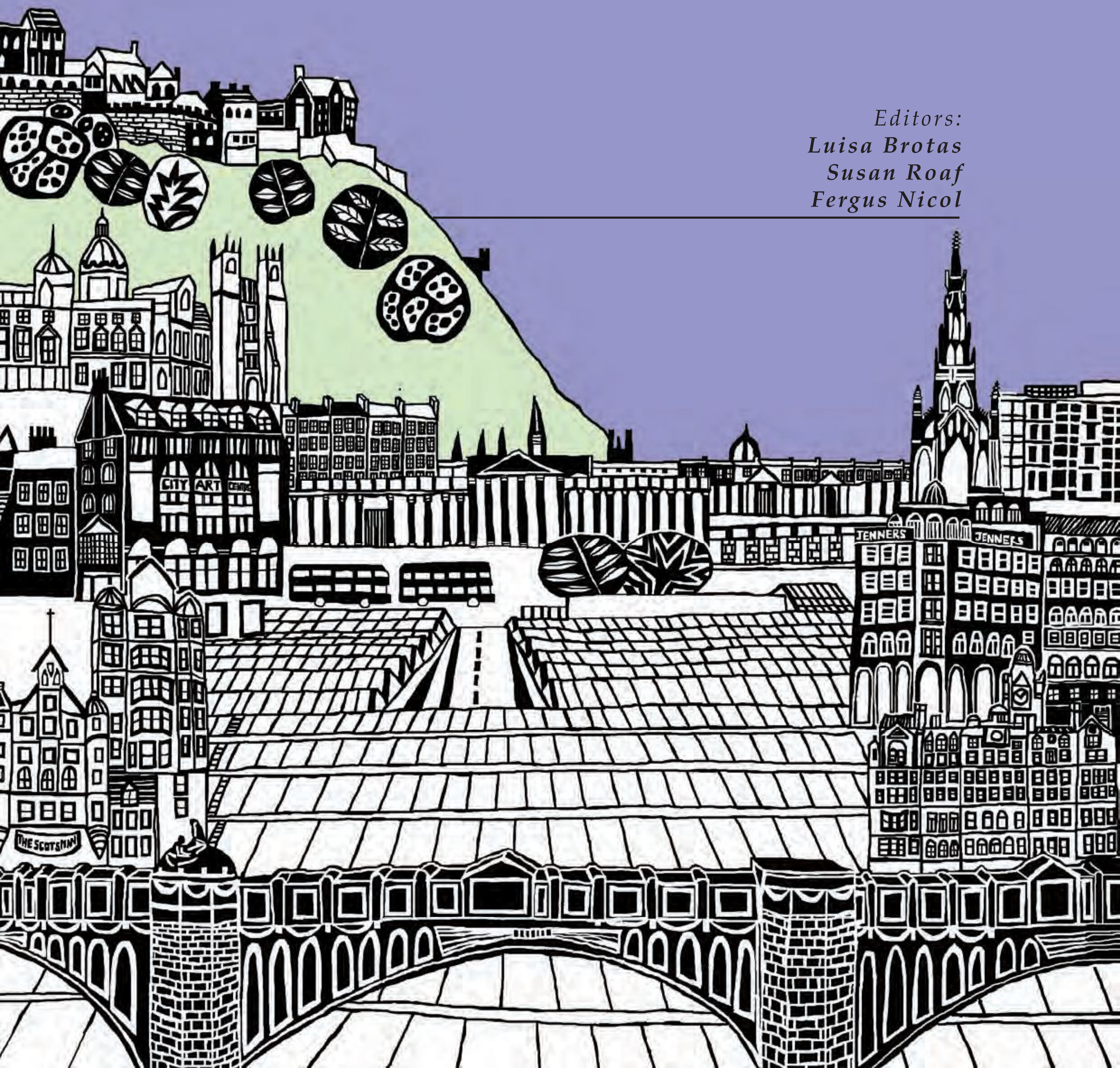

Connecting householders with their homes using low-cost technological interventions

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Abstract: Dampness-related problems at home can put householders' health at risk. Householders often do not know how to use their homes to get the conditions they want. They are unable to understand the complex interplay between humidity, air temperature and ventilation, provoking unhealthy interior environments unintentionally. This paper presents an analysis of problems associated with dampness and householders' behaviour in low-income houses in South Wales. This project aims to help people to understand better how their homes work, and encourage them to strengthen their connection to the indoor environment of their home by using low-cost feedback devices. The study uses off-the-shelf, real-time feedback technology to help householders visualize how their homes respond to their actions. Semi-structured interviews and a focus group were used to identify 'good' and 'bad' practices of home operation. Data-logging equipment was used to measure the physical variables of the indoor environment. The results describe householders' experiences and feedback when using low-cost technological interventions to understand moisture-related problems at home. Some possible triggers for householders' actions are suggested along with other factors that may inhibit people's connections with their homes such as lifestyle, technological skills and knowledge.

Keywords: Post-occupancy evaluation, dampness, low-income housing, people's behaviour, monitoring

Introduction

Indoor dampness has been reported in up to 80% of buildings in studies around the world (Hagerhed-Engman et al., 2009) and in 10-50% of indoor environments in Europe, North America, Australia, India and Japan (WHO, 2009). The most common indicators of dampness at home are visible mould spots, damp stains, damp clothing/or bedding, condensation and water damage on walls and windows, and mouldy odours. Moulds grow at different temperatures including interior temperatures that people prefer. The largest group of mould (mesophilic fungi) has an optimum temperature range of 15-30°C (Godish, 2001). Black mould is a visible indicator of long-term dampness problems; it grows in environments with constant relative humidity (RH) above 70%. Exposure to black mould can cause allergic reactions, asthma attacks, eye and skin irritation, hay-fever symptoms and other serious respiratory problems (EPA, 2016).

There are different causes of high RH in the home. Examples of dampness caused by *house structure and design* are poor cladding details, lack of waterproofing and insulation in external walls, ceilings and windows, poor maintenance, unsuitable use of materials (e.g. latex paints and vinyl wallpapers), lack of extractor fans, and low air change rates. High levels of dampness are often associated with older homes, depending on the year and method of construction (EPA, 2013). Householder's behaviour also plays a significant role. Poor operation of building elements, the heating system and home appliances can cause condensation unintentionally. In addition, householders are often not aware of the interaction of physical factors in their homes (i.e. air temperature, air humidity, evaporation, condensation, etc.) that often underpin dampness problems. The aim of this research, therefore, is to identify householder's behaviour that may cause dampness problems and to consider whether low-cost monitoring intervention can help people to better understand their indoor environment and encourage necessary changes in behaviour.

Methodology

Case studies

The research was conducted in Merthyr Tydfil within the Brecon Beacons National Park. The climate in Merthyr Tydfil is warm and temperate with significant rainfall for most of the year. From October to January, monthly rainfall can exceed 250 mm. The warmest month is July (average 19.4 °C) and the coolest, February (average 0.5 °C) (Met-Office, 2016). The study was developed in two stages: a summer and a winter study. Nine houses (H-1 to H-9) were selected for the study. Six houses participated in summer and six in winter (Figure 1).

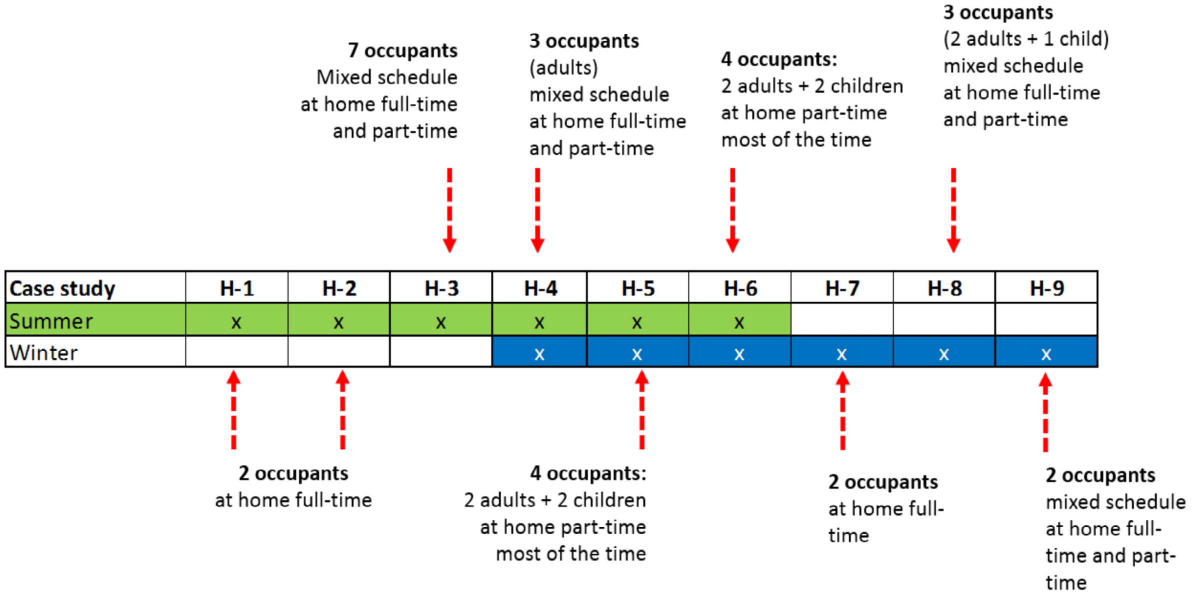

Figure 1 Description of the case study houses

All houses have a similar structure and layout (2 floor-storey terrace houses) and were built around 1890. The orientation and number of family members differed. House size varied from 60 to 100m^2. In summer, the study was designed to identify householders' activities that could explain some causes of dampness. For this reason, the six houses were divided in two groups: the *control group* had houses with very limited or no dampness problems (H-1, H-2 and H-3). The *intervention group* had houses with dampness problems reported by householders (H-4, H-5 and H-6). During winter, six houses were analysed, extending the analysis of householders' behaviour in houses with dampness problems. Three new cases with dampness problems were included (H-7, H-8 and H-9), replacing the previous houses without problems.

Physical measurements

Physical measurements of the homes included: air temperature, RH, indoor air quality, and energy use. Two types of monitoring device were used in the experiment. The first type was used to gather accurate information about physical variables. Air temperature and RH were measured with *HOBO U12-013*, energy use with an *efergy E2* classic clip-on electricity monitor and CO_2 levels with a *Telaire T7001* connected to a *HOBO U12-013*. Total Volatile Organic Compounds (TVOC), formaldehyde and Total Mould Volatile Organic Compounds (TMVOC) were measured with in a laboratory from samples drawn using a pump and a glass tube. The second type of monitoring used proprietary feedback devices to help householders visualise air temperature, air humidity and energy use in their homes (Low-cost therma-hygrometers with colour indicators and thermometer gauges). During summer, physical measurements included air temperature, RH and electricity use only, whereas in winter, $CO_{2,}$ formaldehyde, TVOC and TMVOC were added. Climatic conditions of the exterior environment were collected from a weather station located in the centre of Merthyr Tydfil operated by Miller Argent.

In summer, the monitoring period started in the second week of August 2016. Householders in the control group did not have access to the equipment displays or other information, they were asked to carry out activities as normal. The monitoring of the control group continued uninterrupted until the end of the study. The intervention group had two monitoring periods: before and after intervention. The intervention consisted of providing low-cost monitoring devices to householders, to visualise air temperature, RH and energy use in real time. The devices include: three therma-hygrometers and three temperature gauges installed in the kitchen, bathroom and either living room or dining room, and one stand-alone energy monitoring display located in the kitchen or living room (Figure 2).

Figure 2 View of the monitoring equipment after installation. (1) CO2 monitoring, (2) electricity meter, (3) therma-hygrometer, (4) temperature gauge and (5) HOBO datalogger.

The energy monitoring display was allowed to be seen by the intervention group only after the second week of the monitoring period. The measurements stopped at the same time in all the properties. In winter, the monitoring equipment and low-cost devices were installed in the living or dining room, bathroom, kitchen and a bedroom. The monitoring period lasted five weeks, from December 2016 to the first week of January 2017. Householders were allowed to see the equipment displays to provide feedback about their interaction with them and their understanding of their homes. CO_2, TVOC, formaldehyde and TMVOC were also measured in the living/dining room.

Qualitative methods

Semi-structured interviews were used to identify the householders' behaviours in their homes and their understanding of the connections between their actions and the resulting indoor environmental conditions. Householders' demographics, lifestyles and behaviour at home were also analysed. All householders were interviewed at the start of the project to identify 'good' and 'bad' practices in each home. *Good practices* were considered as activities that help to reduce or control dampness problems in the indoor environment. *Bad practices* were considered as activities that increase the accumulation of water vapour in the indoor environment creating or increasing dampness problems at home. At the end of the monitoring period, a focus group was organised to collect feedback and experiences from the intervention group. In winter, householders were encouraged to write notes of dampness problems during the study. They were also interviewed at the end of the monitoring period and asked to explain with a diagram using post-its how the heating system works and the main use of the thermostat at home.

Results and discussion

During the monitoring period, Merthyr Tydfil had high exterior humidity: summer mean was 75% (min=37, max=92, SD=14) and winter mean was 83% (min=15, max=97, SD=13). RH values during summer in houses with dampness problems were 70% and up to 99%. In winter, RH was 50-60%, except in rooms with serious dampness problems. Lower RH in winter could be due the use of the heating system or the effect of the exterior microclimate.

Identified dampness problems

During summer, black mould was found mostly in room corners on north facing and end-of-terrace external walls. It was visible in bathroom corners, kitchen corners, entry ways and under stairs. During winter, the majority of the spaces in the houses, mould was observed in corners of bathrooms and under stairs in similar quantities as in summer. However, two end-of-terrace houses were the most affected by mould with a noticeable increase (wall area) from summer to winter. In H-4, new black mould spots were found in wall corners and around the pipes in the living room. In H-5, new black mould spots (up to $2m^2$) were found in all areas connected to the end-of-terrace wall. In H-6, black mould and damp stains were visible on walls (bathroom and kitchen) and a mouldy odour was found in kitchen cabinets. New spots were visible on walls behind the door (600 x 600 mm) behind the WC (600 x 600 mm) and behind the lavatory (300 x 700 mm).

Identified 'good' and 'bad' practices during summer

In summer, common practices in houses with few dampness problems were: opening windows daily, cleaning and tidying spaces, using the kitchen/bathroom extractor fan, using the heating system on cold days and closing doors and windows. Although these activities are common, their frequency can make a difference on the indoor environment.

Opening windows was one of the major indicators of good practice. Opening windows every day for a few hours, and while showering, increases ventilation of the house, allowing water vapour to go out instead of being absorbed by materials in the house (carpet, rugs, clothes, wallpaper, etc.). *Cleaning everyday* helps to eliminate mould spores and reduce expansion — black mould needs at least 2 weeks to start growing. Research conducted in China also refers to daily cleaning practices reducing dampness indicators (Liu et al., 2015). *Tidying the house* reduces humid microclimates inside the house, typically in corners. *Using* *extractor fans* helps to speed up the expulsion of water vapour from the kitchen and bathroom. *Closing the kitchen door and bathroom door* during certain activities helps to isolate humid areas. *Wiping droplets from the windows* helps to eliminate water, so that it cannot be absorbed by other materials. *Turning on the heating for a few hours* in very cold days helps to keep walls and materials dry, reducing water activity values of surfaces and moving away from optimal conditions for mould growth.

> *(H-1) …"We hoover every day, twice a day if I've got my grandkids"… (Window droplets) …"needs a clean regular, about once a fortnight"…*

Although in some cases householders were conscious of the effect and importance of their actions in relation to the dampness problems, in other cases their actions were related to other personal reasons. For instance, some householders spend more time at home (full-time) than other householders (part-time), which allows them to open the windows for longer. The number of occupants can also influence the use of appliances and activities generating water vapour (cooking activities, shower, tumble dryer, etc.). Health problems also influence how householders use their homes. For instance, the main reason why householders in H-2 showed a careful schedule of opening windows is due to a chest problem and the need to get fresh air continuously. In another example, the kitchen door was closed to prevent smells from going to other areas of the house. Bad practices in houses with dampness problems were also related to personal factors. In houses with dampness problems householders felt cold during the summer, and so do not open windows. This creates a vicious circle, increasing humidity levels and thermal discomfort. In some cases, relative humidity inside was higher than the exterior. In a sample week RH in the kitchens and bathrooms was 80-90% (Figure 3).

Pet birds, cats, dogs and fish were found in most homes. Although keeping fish has been associated with visible damp stains and window condensation (Liu et al., 2015), the effect of other pets on house operation needs further investigation. In one case the kitchen door is left open at all times to allow visual communication with pets; in another case, opening windows 24/7 allows cats to enter and leave the house with freedom.

> *(H-4) …"We've got two cats they are the main pets, and then … there are two cats, one belongs to a neighbour that is about six houses down, that goes in and out…we just left the bathroom window open so that they can come and go"…*

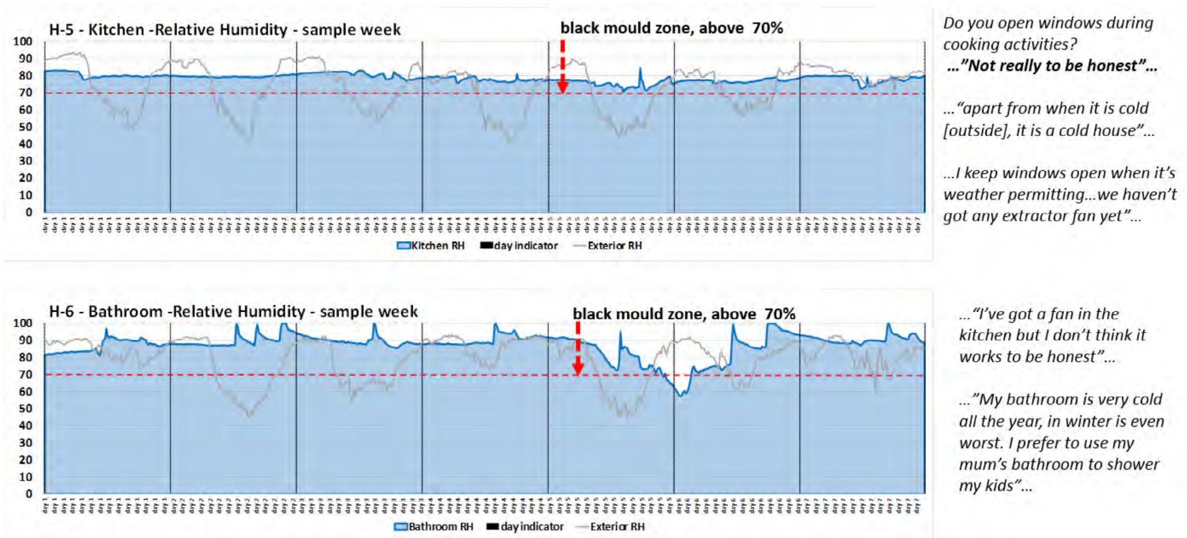

Figure 3 Relative humidity in a kitchen (H-5) and a bathroom (H-6) in end of terrace houses during a summer sample week next to quotes that illustrate the householders reported actions.

Additional problems identified during winter

During winter, householders do not open windows, windows are only opened for short periods during cooking and after taking a shower. The indoor air quality test revealed that limited ventilation practices at home can increase levels of CO_2 and VOC. Most of the houses measured in winter had CO_2 levels above the target 800 ppm and above the maximum recommended 1000 ppm (Figure 4). Continuous CO_2 values above these limits, suggest poor ventilation practices that may result in unhealthy indoor environmental conditions in the long term. Elevated (1500-3000 µg/m^3) and severe (> 3000 µg/m^3) VOC levels were also found in most houses (Figure 5). An air test to identify mould spores was conducted in the living rooms, results revealed that mould spores were minimal (<8 µg/m^3) and active-moderate (8-30 µg/m^3) at the beginning of winter.

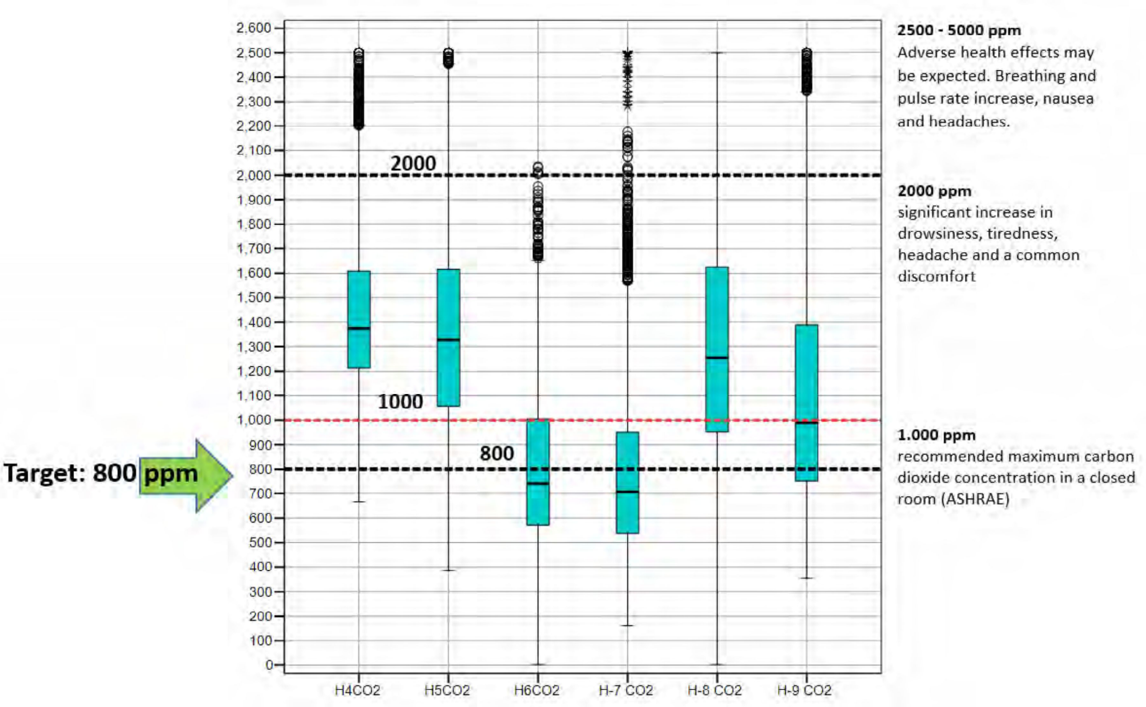

Figure 4 CO_2 levels in the living rooms during winter

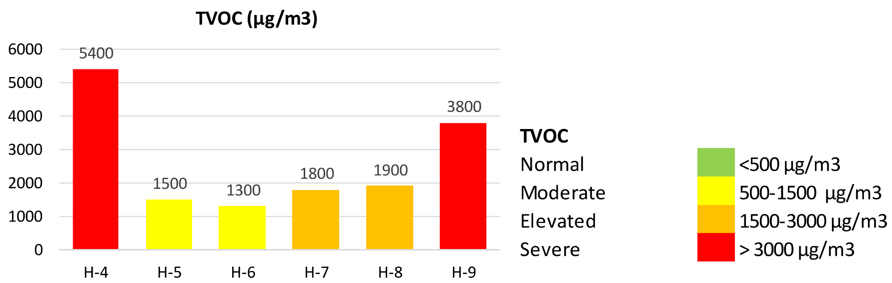

Figure 5 Levels of Total Voltaic Organic Compounds (TVOC) measured in the living rooms during winter

Householders' experience with the monitoring kit

The research was too short to witness a notable change in householders' behaviour. However, the few weeks allowed them to explore their home and understand the effect of some practices (e.g. opening windows) on indoor conditions.

(H-5) … "It was interesting to know about the humidity levels, what it's like upstairs compared to downstairs, it's interesting to see that because I can see what are the worst areas. I was told that the bathroom would probably be the worst because of the tumble dryer, but it's actually not. The kitchen is the worst, then it's here (living room)"…

Different householders showed various levels of interest in, and engagement with, the equipment. All of them could provide information on the physical measurements in different rooms. In all cases, householders were very interested to see the humidity values in the different rooms and to refer to a humidity value to assess their house.

(H-6) …"The dining room and my bathroom didn't move off the wet dial at all, even when it was really sunny outside, even when my heating was on. The humidity levels were very high, constantly, and it hasn't gone below 86… And I could see by the humidity levels, especially my bathroom, it didn't go below 99, at all"…

Some householders could also reflect on the effect of their actions such as opening windows and closing connecting doors.

(H-5) …"I learned quite a bit, you know, from watching it because I'd play with the windows, you know, I'd open the windows more frequently to see if it'd make any change or anything in the back… There were two days specifically that I opened the windows just to see if it'd make a difference…"

…"Once I was cooking, I noticed the humidity levels went up. When the shower was going it went up…I could tell (during which activities it went up)… like with the tumble dryer, it didn't go up by much but with the shower it went up by a lot, even though the window was open it still went up quite high. Not as high as the kitchen, which was, 95% was the highest"…

During summer, all participants mentioned that they were more interested in measuring humidity rather than electricity, whereas during winter the focus of their attention was on air temperature. Overall, all of the householders were more interested in measuring relative humidity and air temperature rather than electricity.

(H-6) …"To me, if I look at that (electricity meter display), I don't really understand it, it doesn't mean a lot to me… whereas that (digital thermo-hygrometer) is quite easy to read, you understand it"… …"Kilowatts and things like that I don't really understand to be honest"…

Conclusions

This study aimed to help householders connect their actions to indoor environmental conditions at home, with a focus on the management of RH and dampness. Providing householders with suitable instruments can help some of them increase their understanding of how their dwellings work and the impact of their behaviour on the indoor environment. In this study, the householders provided with monitoring equipment showed a better understanding of their homes. The monitoring of humidity and temperature had a larger impact than electricity monitoring on householders' behaviour, and attracted greater interest from them. The preferred device was the therma-hygrometer, as it was easier to use, no buttons, provided immediate feedback and simple visual information with colours. With this real time feedback, at the end of the study, participants were able to give information about the temperature and humidity in their homes including numbers and percentages. However, during the implementation of new technologies, such as hygrometers, thermostats, energy meters it is important to take into account people's different levels of technological literacy. Householders need to understand what units, like kWh, RH% and CO_2 mean, and provide them with their preferred ways to visualize the information. The way that householders interact with their home is also shaped by different personal factors such as health, pets, occupancy (part-time/full-time residents), family size and access to windows, etc.

Householders using the house part-time during the week (i.e. after work) could be limiting the time the windows are open. Householders who see their house as 'cold' avoid opening windows, this creates a vicious cycle, increasing humidity levels indoors and creating a cold environment suitable for mould to grow. It is advisable that interventions considered the lifestyle and preferences of the occupants to identify the solutions that are suitable to their routines. Overall, in winter and summer householders were interested in visualising the discomfort that they can sense but can't see, for instance relative humidity, air temperature, black mould, mouldy odours, unpleasant odours, and unpleasant stuffy interior environments. Practical workshops and suitable visual training and information for householders need to be implemented continuously as 'preventive actions'.

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