Understanding indoor environmental conditions and occupant’s responses in houses of older people

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Abstract. In Australia, the vast majority of older people, those aged 65 years and over, want to live at their own homes for as long as possible. Older people are, however, vulnerable to extreme conditions, hot or cold, and therefore it is crucial to ensure that the home’s indoor environmental conditions are conducive to their health and well-being. The first step to do this is by understanding the existing conditions in homes of older people so that appropriate steps for improvements can be taken. This paper presents an on-going study to understand the indoor environmental conditions and occupant’s responses in homes of older people in South Australia. The study is conducted using a robust indoor environmental monitoring system that is integrated with a user-friendly occupant survey system using an electronic tablet, allowing the occupants to reflect on their “right here right now” experience over different seasons in a year. The paper discusses the development of this integrated system and reports some preliminary data. Preliminary results showing the associations between measured environmental data, such as dry bulb temperature, radiant temperature, air velocity, and CO2 level, and thermal sensation, comfort, perception of indoor quality and self-reported health/well-being will also be presented.

1. Introduction

It is well known that temperature is an environmental factor that significantly impacts human thermal comfort [1, 2]. An extensive body of literature has also shown significant relationships between temperature and mortality [3, 4] as well as between temperature and morbidity [5, 6]. Exposure to high temperatures can lead to cardiovascular consequences, hyperthermia and heatstroke, which can be fatal [7, 8], while cold temperatures can also lead to cardiovascular and respiratory diseases as well as hypothermia [9, 10]. Parallel to these studies, a large-scale study in the US found a significant relationship between ambient temperature and well-being, with positive emotions (e.g. joy, happiness) decreasing while negative emotions (stress, anger) and fatigue (feeling tired, low energy) increasing at ambient temperatures above 21 °C [11]. These studies indicate that ensuring that our living environment is not too cold or not too hot is not only important to maintain thermal comfort, but also critical to ensure that we maintain positive well-being and are not exposed to conditions that can be fatal to our health.

Numerous reports have shown that as people age, they become more vulnerable to extreme heat or cold [12]. This is because as people age, their ability to detect changes in their thermal environment decreases due to reduced muscle strength, which results in lower metabolic rate, decreased thermoregulatory response, lower cardiovascular flexibility and decreased heat tolerance [13, 14]. A recent thermal comfort study of older people by Bills [15] found that neutral temperatures of the participants during winter mostly occurred at indoor operative temperatures that were lower than the lower end of acceptable temperatures as suggested by ASHRAE 55 At the same time, the participants reported experiencing the least health symptoms at indoor temperatures between 21 and 24.3 °C [16]. This means, while they accepted a cooler condition than suggested by the standard, the condition might actually pose a higher health risk compared to heating their houses to be warmer.
A study is currently being undertaken, aiming to understand the indoor environmental conditions in existing housing of older people in South Australia so that lessons learned will help improve design guidelines and relevant policy for future housing. The first stage of the study involved a general survey of a randomly selected sample of 250 older people from three climate zones in the State (semi-arid, warm temperate, and mild temperate), aimed to understand the occupant’s thermal behaviours and investigate whether there were associations between climatic conditions, internal environmental conditions, housing types and constructions, heating and cooling behaviours and the occupant’s health and well-being [17]. The second stage involved a series of focus group discussions with older South Australians, to understand the indoor environmental qualities of the existing living environment, the strategies undertaken to be comfortable, and existing problems related to planning and house design [18]. The third stage involves an indoor environmental monitoring and survey of 53 households, recruited from the survey and focus groups above. The paper focuses on discussing how the relevant data are acquired. It will also present some preliminary results.

2. Data acquisition and survey tools

To understand the conditions at different times in a year, studies of the indoor environmental conditions of homes are usually conducted over a relatively long period, between 3 to 12 months. Therefore, due to the long study period, small, unobtrusive and self-contained data acquisition devices are best used to ensure that they are not interfering with the occupants’ regular activities and not contributing to the occupants’ electricity usage, for example [19, 20]. Along with the collection of the indoor environmental parameter data, occupants are normally asked to respond to an indoor environmental survey. Many studies use paper-based survey forms while others use on-line using computers or smart phones, for example [21]. The challenge of such data acquisition and survey methods is that both types of data collected (i.e. from the indoor environmental parameters and the occupant’s survey responses) have to be merged manually by the researcher in order to analyse the relationships between the survey responses and the various parameters at the time the occupant respond to the survey. Using paper-based survey forms also poses an additional challenge as it relies on the researcher’s diligence to transfer the information into a readable format for further analysis. The survey participants may also accidently, or intentionally, skip some questions, thus resulting in incomplete survey responses.

The data acquisition and survey tools developed for this study are based on previous work by the authors [22], and modified to be suitable for use by older participants. The underlying principle is that the tools must be: (1) robust, (2) unobtrusive, (3) do not rely on the occupant’s electricity (or internet connection), (4) user-friendly, and (5) low cost to meet with the available budget, particularly because 60 sets of the device were required (60 environmental data loggers and 60 survey tablets).

2.1. Indoor environmental conditions logger

The indoor environment conditions logger consists of sensors which assess air temperature, globe temperature, air speed, relative humidity, CO2 and VOCs. The logger coordinates measurements from the sensors, undertaken at 30-minute intervals and when a participant completes a comfort survey. Measurements are stored locally in text files on a Secure Digital (SD) card of 8 GB capacity. The logger incorporates a XBee (Digi) radio which allows communication with the environmental survey tablet and a 3G cellular modem for communication of data to the internet. The cellular modem is used to transmit a data file containing time stamped participant surveys and logger measurements to an external FTP (File Transfer Protocol) website once per day. The approach of storing data locally (SD card) and transmitting data to the internet provides a useful degree of storage redundancy.

The logger architecture is based on the Atmega 328 microprocessor (Attel Systems Corporation) and employs an Arduino derived development board (Seeeduino Stalker V3.1). The board incorporates a Real Time Clock (RTC) which is battery backed in case of loss of power. Connections between the board and the various components is achieved using a Printed Circuit Board (PCB) which was custom fabricated for the purpose. The PCB also manages the power supply for the logger which is provided by a 20,000 mAh power bank (Xiaomi), giving a theoretical battery life of 6 months. Firmware, written using the Arduino Integrated Development Environment (IDE) in a version of C++, controls the core functions of the logger and survey tablet. The logger is then placed in an enclosure (Figure 1). After
consulting the participants, the logger is normally installed in the most used living area of the house, at a height of 0.8-1.2m from the floor, on a horizontal surface (e.g. table or shelf) as close as possible to a chair that is frequently used by the participant.

2.2 Indoor environmental survey tablet
The environmental survey tablet is intended to allow participants to complete comfort surveys electronically, once a day if possible, or at least twice a week. The main component is a 7” touch screen (Nextion by Itead). To commence a survey a participant ‘wakes’ the tablet by pressing the button below the screen, after which the tablet switches on and the first survey question is presented (Figure 1, centre). At the completion of the survey, the screen switches off and the survey responses are transmitted wirelessly to the logger where they are time-stamp recorded along with environmental measures taken within five minutes or less of the survey response. The tablet is controlled by the same type of Arduino development board (Seeeduino Stalker V3.1) which is connected to the screen, button and power supply by the same PCB. Radio communication is undertaken by paired XBee radios and power is supplied by an identical 20,000 mAh power bank (Xiaomi). Firmware for the tablet is different to that employed on the logger however was developed in the same fashion. Each tablet is secured in a custom-made laser-cut acrylic enclosure. A strong handle was then added so that the participant can easily lift it up or carry it around.

![Figure 1. The new indoor environmental logger and survey tablet](image)

2.3 Indoor environmental survey questions
The survey questions are either multiple-choice questions (e.g. Are windows in this room: all close, some close/open, all open), on 5 to 7-point scale (e.g. Do you feel: cold, cool, slightly cool, neutral, slightly warm, warm, hot), or requiring yes/no answer (e.g. the heater is: on, off). See Table 1. Both the text and appearance of the questionnaire on the tablet were discussed with and trialled by three groups of older people to ensure clarity of the questions and usability of the interface.

2.4 Operation and communication
Once per day, each logger transmits a text file containing time stamped measurements and survey data to a FTP website. The file is stored in a directory linked to the logger’s unique telephone number which relates to the 3G modem and SIM card employed by the logger. Beyond the phone number, neither the data file nor the loggers contain any identifying information. Researchers are able to access data files on the FTP site which are named based on the date when they were created by the logger. As each logger transmits a file once per day, it is an easy exercise (albeit stressful) to identify if a logger may have stopped working, which in turn provides the opportunity of timely corrective actions to be undertaken. The rigid structure of the logger file structure also facilitates aggregation of files for analysis purposes. Files can be quickly downloaded and aggregated using simple batch scripts for more detailed analysis.

3. Sample of results
In order to analyse the data collected daily, software scripts have been prepared to automatically: (1) collate all the indoor environmental parameters from each house as well as from all houses, and (2)
Table 1. Summary of indoor environmental survey questionnaire

| Type                                      | Questions                                                                 | Answers                                                                 |
|-------------------------------------------|---------------------------------------------------------------------------|-------------------------------------------------------------------------|
| Identification                            | Person No: Person 1, Person 2                                              |                                                                         |
| Which room are you in?                    | Person 1, Person 2, Living room, Bedroom                                  |                                                                         |
| Thermal comfort related questions         | How are you currently dressed?                                            | Very light, Light, Moderate, Heavy, Very heavy                           |
|                                           | Describe your activity in the last 15 minutes in this space:               | Very relaxed, relaxed, light, moderate, active                          |
|                                           | How do you feel right now?                                                | Cold, Cool, Slightly cool, Neutral, Slightly warm, Warm, Hot            |
|                                           | Would you prefer to be...                                                  | Cooler, No change, Warmer                                               |
|                                           | How satisfied are you with the temperature in this room?                  | Very satisfied, Satisfied, Partially satisfied, Dissatisfied, Very dissatisfied |
| Heating, cooling, ventilation related    | The air conditioner in the room is...                                     | On, Off                                                                 |
| questions                                 | A heater in this room is...                                                | On, Off                                                                 |
|                                           | A fan in this room is...                                                   | On, Off                                                                 |
|                                           | Curtains / blinds in this room are...                                     | All open, Some open/close, All close                                    |
|                                           | In this room, windows and door(s) to outside are:                         | All open, Some open/close, All close                                    |
|                                           | In this room, door(s) to other room(s) are:                               | All open, Some open/close, All close                                    |
| Air quality questions                     | Do you think the air in this room is...                                   | Stuffy, OK, Draughty                                                   |
|                                           | Do you feel that the air quality in this room is:                         | Very good, Good, OK, Poor, Very poor                                   |
| Health/well-being related questions       | How would you describe your health and well-being at the moment?         | Very good, Good, Reasonable, Poor, Very poor                           |
|                                           | The conditions in this room influence my health and well-being:           | Definitely yes, Probably yes, Yes, Unsure, Probably not, Definitely not |

collate the survey responses as well as indoor environmental parameters from each house as well as from all houses. While the study only commenced in mid-January 2019, the sample results below demonstrate the richness of data that can be collected from the logger and survey system; however, due to space limitation, only a selection of results from the entire samples are presented here.

Until 14 March 2019, a total of 2121 survey responses have been collected. Figure 2 shows the histogram of the time of day when the participants responded to the survey. Almost 60% of the responses occurred from midnight until before 5pm. Figure 3 shows the indoor operative temperatures at the time the participants responded to the survey and the time of occurrence, binned by 1 hour intervals. It is interesting to see that some participants responded to the survey even at the early hours before 6 am.

Figure 2. Histogram of percentage of responses

Figure 3. Indoor operative temperatures during the survey

Figure 4 shows the histogram of the indoor operative temperatures, binned by 1 °C intervals, at the time the participants responded to the survey. The mean indoor operative temperature and standard deviation was 23.9 °C (2.59) while the maximum and minimum were 36.2 °C and 14.4 °C, respectively. During this time, only 13% of the time participants reported to be using an air-conditioner and only 11%
reported to use fans when they responded to the thermal comfort survey. Figure 5 shows the thermal sensation votes (TSV) from all participants during this period. The neutral sensation was reported 46.4% of the time, while 33.7% of the time they reported to be slightly cool to cold, and only 19.9% of the time they felt slightly warm to hot.

Figure 4. Histogram of binned indoor operative temperature

Figure 5. Percentage of thermal sensation votes

Figure 6 presents the indoor operative temperature and TSV, while Figure 7 illustrates the average TSV calculated for every 0.5K of indoor operative temperature with a regression model fitted using weights according to the number of votes in each bin. The fitted model indicates temperature neutrality of 25.4 °C. This is 2.7 °K higher than the neutral temperature found in an earlier study in Adelaide during summer months but with younger adults [23]. The thermal sensitivity of 0.127/K seen in Figure 7 can also be compared to earlier studies of general populations in South Australia which produced thermal sensitivity of 0.247/K and 0.185/K [23, 24]. These comparisons could indicate that the older participants had a reduced sensitivity to temperature variations and/or might have better adaptive strategies.

A strong association was found between the air movement in the room (too stuffy, OK, or too draughty) and the perceived air quality (\(p = 0.000\)), with the highest level of air quality reported when the air was not too stuffy or too draughty. Chi-Square tests of the data also indicate that the ‘very good’ air quality was felt when the windows and doors were mostly opened. A strong association was identified between thermal sensation vote and thermal satisfaction (\(p = 0.000\)), with the highest level of satisfaction experienced during the neutral sensation votes. There is also a strong association between thermal sensation and thermal preference (\(p = 0.000\)).

A strong association was also found between thermal sensation and perception of health and well-being (\(p = 0.000\)), with having ‘very good’ health and well-being occurring mostly at the neutral sensation votes. Analysis of the results also indicates that, for the participants, having ‘good’ to ‘very good’ health and well-being is definitely influenced by the indoor environmental conditions; however, when the participants felt that their health and well-being was ‘poor’ to ‘very poor’, the indoor conditions were not perceived as a major cause of that. In other words, the indoor environmental conditions seemed to have a more positive contribution to the participant’s health and well-being, but were perceived as having less association when they were not in a good state of health and well-being.
4. Lessons learned and conclusion
A robust, unobtrusive, and independent indoor environmental data logger and a user-friendly survey interface have been developed to be used for an indoor environmental study in houses with older occupants. While this study is on-going, the system has so far been able to collect, record and transmit data successfully to the researchers on a regular basis (daily) without fail. The system also allows the researchers to remotely monitor the data collected by the devices, daily, thus reducing the need to travel to each of the participant’s homes. Through a scripting technique, the data transmitted from both devices have been successfully collated and analysed, as shown above.

Some participants, however, occasionally experienced a problem in responding to the survey which had to be done by pressing the relevant answer on the tablet. Using a touch screen seems to pose a challenge for some people with problems in using their fingers due to medical conditions. This issue needs to be looked at more carefully in future studies. Some participants also expressed their concerns over the impact of the electronics within the device and the wireless 3G connection in the logger on their health. This highlights the need to provide sufficient information about the research equipment. While further improvements could be achieved, the study has demonstrated an advancement for collecting data about the living environment of older people. This is a fundamental step in developing new knowledge on how to improve their living conditions and provide better housing for the future.

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