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Identifying a suitable method for studying thermal comfort in people's homes

Vireen Limbachiya[1, 2], Keyur Vadodaria[1], Dennis Loveday[1], Victoria Haines[3]

[1] School of Civil and Building Engineering, Loughborough University, Loughborough, Leicestershire, LE11 3TU, United Kingdom

[2] Current affiliation: Faculty of Engineering and Computing Coventry University, Coventry, CV1 5FB, United Kingdom

[3] Loughborough Design School, Loughborough University, Loughborough, Leicestershire, LE11 3TU, United Kingdom

Corresponding email: k.vadodaria@lboro.ac.uk

Abstract

In the UK, domestic buildings are responsible for a significant amount of overall carbon emissions from buildings. Together with improving the energy efficiency of the existing domestic stock, an in-depth understanding of thermal comfort in homes is necessary to ensure that acceptable levels of thermal comfort are maintained whilst energy use is being reduced. Currently, there is limited knowledge on domestic thermal comfort in the UK as, compared to non-domestic buildings, conducting thermal comfort studies in homes is challenging. Detailed thermal comfort studies are usually considered to be intrusive in domestic environments. Is it therefore possible to conduct thermal comfort studies that are less intrusive and yet scientifically rigorous? With a view to address this question, the study presented in this paper undertook a comparison of two data collection methods. Data collected using a less-intrusive method, referred to as the 'Silver standard' was compared with the data collected using the ASHRAE/ISO recommended method (referred to as the 'Gold standard'). A strong correlation was observed between PMV values obtained using the Silver Standard method and those obtained using the Gold Standard method. The findings suggest that the less-intrusive method devised and tested in this study provides reliable data for thermal comfort evaluations in homes. The findings also suggest that further work is necessary, particularly in winter conditions to comprehensively validate this non-intrusive method.

1.0 Introduction

The existing UK domestic building stock accounts for nearly one third of the total energy consumption of the UK (Figure 1) and as shown in Figure 2, space heating alone is responsible for over 50% of the domestic energy consumption. Since space heating is directly related to the human needs of thermal comfort, a better understanding of people's thermal comfort in their homes is required. Currently, there is limited knowledge on thermal comfort in homes in the UK. The majority of thermal comfort studies have been conducted in non-domestic buildings, mainly offices. Very few thermal comfort studies have been conducted in homes (Pimbert and Fishman (1981), Hunt and Gidman (1982), Oseland (1994), Summerfield et.al. (2007), Hong et.al. (2009), Shipworth et.al. (2010)). In order to develop a better understanding of domestic thermal comfort, large scale studies would be helpful. However, there are challenges in conducting thermal comfort studies in domestic environments. The biggest challenge is to maintain an optimum balance between the scientific rigour of an experiment and the practicality of conducting experiments in privately-occupied houses. Field experiments involving participants often have constraints that limit the extent of control that an experimenter can have on the environment as well as on the participants themselves. Furthermore, the use of measuring equipments, including data loggers, can often cause disruption to the daily life of the participants as well as to other occupants of the house who may not be participating in the experiment. In addition to this, it may not be appropriate for the experimenter to be present at the house for the entire duration of the experiment, as it could be considered intrusive by the householder. Hence the question that needs to be answered is: What is the optimum method for conducting thermal comfort studies in people's homes, particularly while conducting large sample surveys? Based on this research question, the overall aim of this study was to propose and validate a less-intrusive method for conducting thermal comfort studies in homes in the UK.

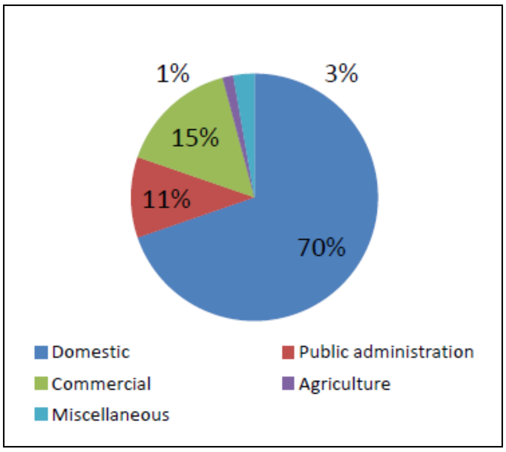

Figure 1: UK Domestic energy consumption in 2008 (DECC 2010)

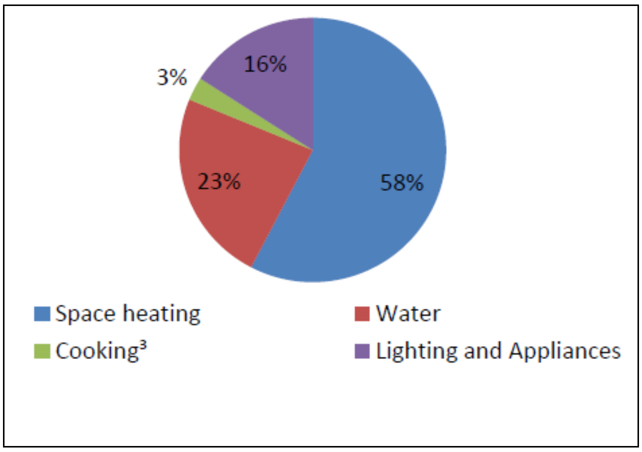

Figure 2: UK domestic energy consumption by end use in 2008 (DECC 2010)

2.0 Methods

The most common method used to evaluate objectively thermal comfort is Fanger's PMV-PPD method (Fanger, 1970). Developed in the 1970s, the PMV (Predicted Mean Vote) and PPD (Percentage of People Dissatisfied) method is based on a steady state model. The PMV values indicate the average thermal sensation of a large group of people when exposed to a given thermal environment. In order to compute PMV, six factors that influence a person's thermal comfort are required to be measured. These comprise of four environmental factors:- air temperature, mean radiant temperature, air velocity and humidity and two personal factors:- occupants' clothing insulation (CLO value) and metabolic rate.

ASHRAE Standard 55 (ASHRAE, 2010) and ISO 7730 (BSI, 2005) present methods for determining and interpreting thermal comfort based on this model. The

ASHRAE/ISO method is referred to in this investigation as 'the Gold Standard method'. It requires the measuring of air temperature, air velocity and humidity at three heights (0.1m, 0.6m, 1.0m) and measuring mean radiant temperature with a 150mm diameter globe at 0.6m height. Laboratory grade instruments, as prescribed by ASHRAE (ASHRAE, 2010), are required to take these measurements. Clothing insulation and metabolic activities are required to be recorded by the experimenter using a standard clothing ensemble list given in ASHRAE and ISO standards.

The non-intrusive method, referred to as 'the Silver Standard method' in this study, consists of collecting a limited amount of information and relying on certain assumptions. Air temperature and humidity were recorded through small sized HOBO data loggers (Figure 3 and Table 1) placed in the room close to where the participant was seated. Air velocity was assumed to be less than or equal to 0.1m/s and mean radiant temperature was assumed to be equal to air temperature. Participants self reported their clothing insulation values using the clothing ensemble list (Table 3). The participants were asked not to take any adaptive actions, remain seated throughout the duration of the experiment and to watch television or read a book, thereby engaging in sedentary activity. Therefore, metabolic rates corresponding to sedentary activity levels were assumed by the experimenter.

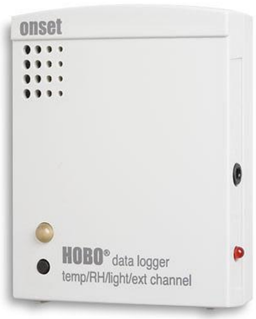

Figure 3: HOBO U-12 Temperature and relative humidity data logger used as a part of the Silver

Table 1: Specification of the HOBO temperature sensors used for the Silver Standard method

Parameters	**Specifications**
Make	HOBO U12 Temp/RH/ logger
Measurement range	-20° to 70°C (-4° to 158°F)
Accuracy	± 0.35°C from 0° to 50°C (± 0.63°F from 32° to 122°F)
Resolution	0.03°C at 25°C (0.05°F at 77°F)
Drift	0.1°C/year (0.2°F/year)
Response time in airflow of 1m/s	6 minutes, typical to 90%
Time accuracy	± 1 minute per month at 25°C (77°F)
Weight	46 g (1.6 oz)
Dimensions	58 x 74 x 22 mm (2.3 x 2.9 x 0.9 inches)

A sample of 17 owner occupied houses located in the Loughborough area in the UK was selected for the purpose of this study. Whilst indentifying the sample, the following considerations were made:

- Ensure an even spread of age whilst selecting participants (age range from 18 to 60)
- Ensure an even mix of gender
- Ensure that the participants had acclimatized to the climate (lived in the UK for at least 5 years)

Details of the sample are given in Table 2.

Table 2 : Details of building and occupants surveyed

Build no	Building type	Participant's gender	Age band of participants
4	End of terrace	Male	20-25
16	Detached	Male	20-25
5	Detached	Male	25-30
6	Semi detached	Male	25-30
15	Semi-detached	Male	25-30
1	Terraced	Male	30-35
8	Detached	Male	30-35
11	Detached	Male	45-50
3	Semi-detached	Male	50-55
13	Detached	Male	55-60
2	Detached	Female	20-25
7	Detached	Female	20-25
10	Detached	Female	25-30
14	Semi-detached	Female	30-35
9	Detached	Female	40-45
17	Terraced	Female	45-50
12	Terraced	Female	50-55

Table 3: Clothing Ensemble List used for the Gold and Silver Standard methods

Clothing	**Clo Value**
T-shirt, shorts, light socks, sandals	0.3
Petticoat, stockings, light dress with sleeves, sandals	0.45
Shirt with short sleeves, light trousers, light socks, shoes	0.5
Stockings, shirt with short sleeves, skirt, sandals	0.55
Shirt, light-weight trousers, socks, shoes	0.6
Petticoat, stockings, dress, shoes	0.7
Shirt, trousers, socks, shoes	0.7
Track suit (sweater and trousers), long socks, runners	0.75
Petticoat, shirt, skirt, thick knee, socks, shoes	0.8
Shirt, skirt, round neck sweater, thick knee socks, shoes	0.9
Singlet with short sleeves, shirt, trousers, V-neck sweater, socks, shoes	0.95
Shirt, trousers, jacket, socks, shoes	1
Stockings, shirt, skirt, vest, jacket	1
Stockings, blouse, long skirt, jacket, shoes	1.1
Singlet with short sleeves, shirt, trousers, socks, shoes	1.1
Singlet with short sleeves, shirt, trouser, vest, jacket, socks, shoes	1.15
Shirt, trousers, V-neck sweater, jacket, socks, shoes	1.3
Underwear with short sleeves and legs, shirt, trousers, vest, jacket, coat, socks, shoes	1.5

3.0 Experimental plan

The experimental plan adopted for this study was as follows:

1. Before commencing the experiments, the participants were met at their home and the study was explained to them in detail. Their consent was obtained using a participant consent form. This was done in accordance with the guidelines set by Loughborough University's Ethical Advisory Committee.
2. After obtaining consent, a HOBO temperature and humidity data logger was placed in the living room of the house, such that it did not interfere with the day-to-day activities of the household.
3. The participants were asked to carry out sedentary activities, like watching their usual TV programme or reading a book, for about 60 minutes and then to fill in the questionnaire towards the end of the experimental session.
4. By means of this questionnaire, the participants were asked to report on the following:

    a. Their thermal comfort on a scale of -3 ('Cold') to +3 ('Hot'), 0 being comfortable/thermally neutral.
    b. How they rated their environment on a scale of 0 ('Comfortable') to 4 ('Very Uncomfortable')
    c. Thermal preference: How they would prefer to be on a scale of -3 ('Much Cooler'), to +3 ('Much Warmer'), 0 being 'no change'.
    d. Thermal acceptability: How they judge their personal environment from 'Clearly Acceptable' to 'Clearly Unacceptable'.

e. Whether they got up from their seat during the 60 minutes and if so, for how long.
f. The clothing insulation values at the time of the experiment.

5. Once the 60 minutes were over, the experimenter returned to the property and asked the participants to complete the same questionnaire for a second time.
6. While the participants were completing the questionnaire for the second time, the experimenter took detailed measurements of air velocity, mean radiant temperature, humidity and air temperature, in order to obtain data in accordance with the Gold Standard method, as described earlier. The experimenter also noted the items of clothing that the participants were wearing and also made a note of their activity levels.

Overall, each experimental session lasted for approximately 75 minutes. Figure 4 below shows examples of the Silver Standard and Gold Standard methods being used at the participant's living room and Figure 5 shows the detail of the measuring equipment used for the Gold Standard method.

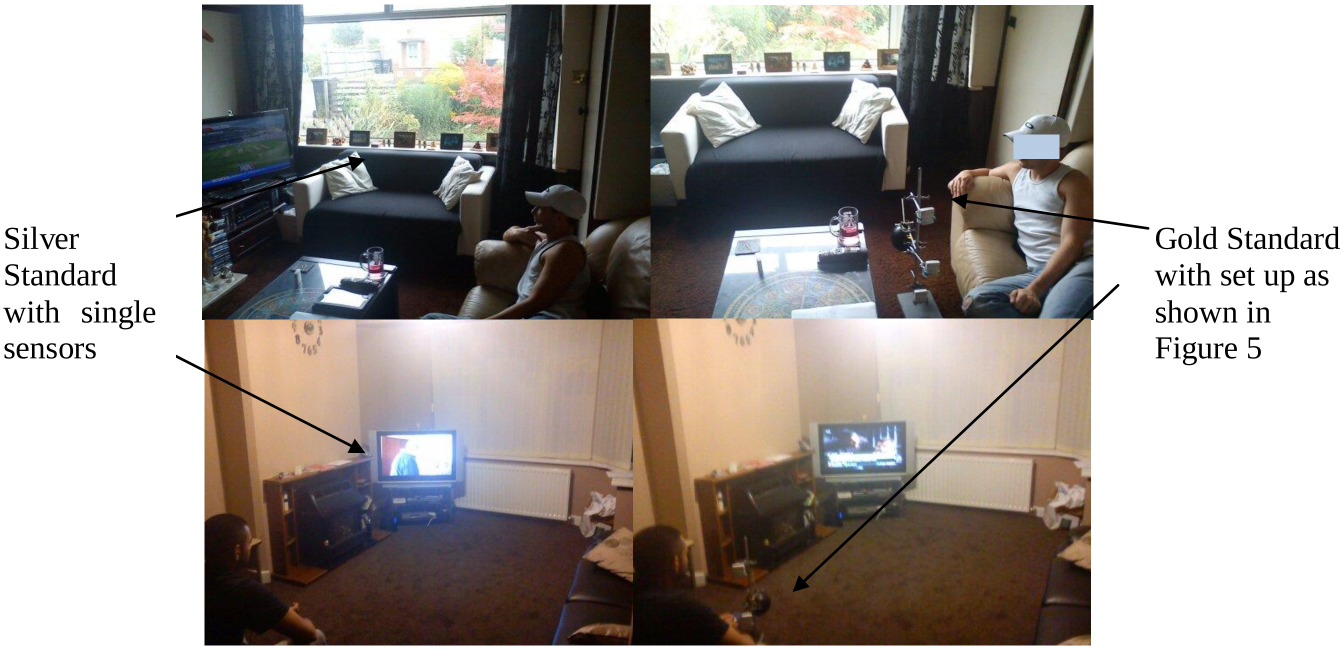

Figure 4: Set up of equipment in the Silver and Gold Standard methods

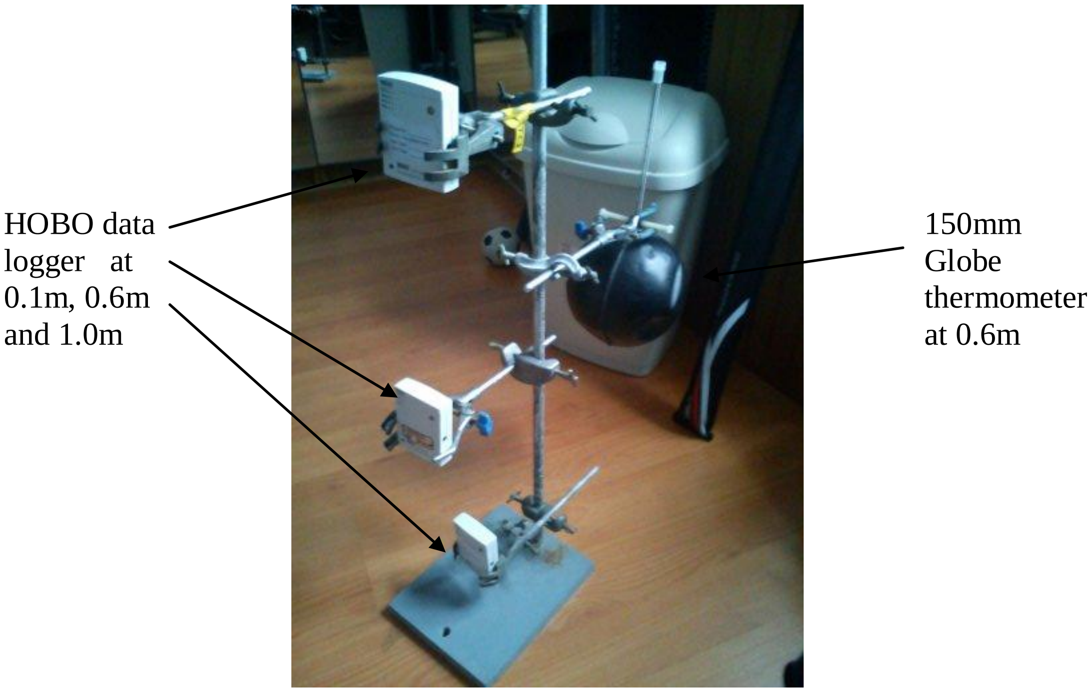

Figure 5: Detailed view of the equipment setup for the Gold Standard method

The following values, taken from Oseland (1994), were added to each participant's clothing insulation value in order to account for the insulation of their seating:

1. Chair = 0.17 clo
2. Sofa = 0.22 clo

4. Findings

The data collected were analysed with the objective of comparing values from the Silver Standard method against the Gold Standard method, hence determining the extent to which the Silver Standard method is valid for domestic thermal comfort assessment. Although the study was conducted in 17 households, the results are based on an analysis of data collected from 16 households. This is because one of the data loggers that was used for the Silver Standard method developed a technical fault whilst recording, resulting in loss of data. This highlights the risk associated with using a Silver Standard method in field studies as opposed to the Gold Standard method, where the use of three separate data loggers minimises the risk of losing data.

4.1 Air Temperature

The first assumption that was made in the Silver Standard method was that air temperature measured at only one height and in the centre of the room will be the same as air temperature measured at three heights and close to the seated participant, as recommended by ASHRAE/ISO. Overall the results shown in Figure 6 show that the Silver Standard method overestimated air temperature by about 1°C as compared to the Gold Standard method.

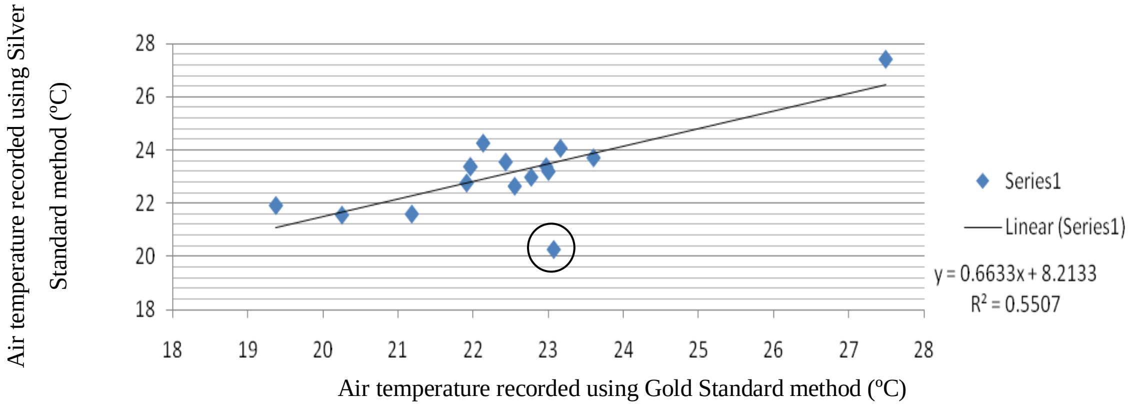

Figure 6: A regression of indoor air temperature measured using the Silver Standard method vs. indoor air temperature measured using the Gold Standard method (includes data from all 16 houses).

Furthermore, a relatively weak correlation (R^2= 0.55) was observed between air temperature recorded by both methods. However, an anomaly was observed in the data collected from one house (house number 6, circled in Figure 6). The room in this house had a layout which consisted of a sofa adjacent to a window that had a radiator below the window sill. As a result of this configuration, the local environment around the sofa was completely different from the rest of the room. By taking this anomaly out of the results (Figure 7), the R^2 value between both methods increased to 0.82 leading to the conclusion that the air temperature could be adequately obtained from the Silver Standard method as long as the layout of the room does not leave the environment around the seated occupant as being significantly different from that in any other point in the room.

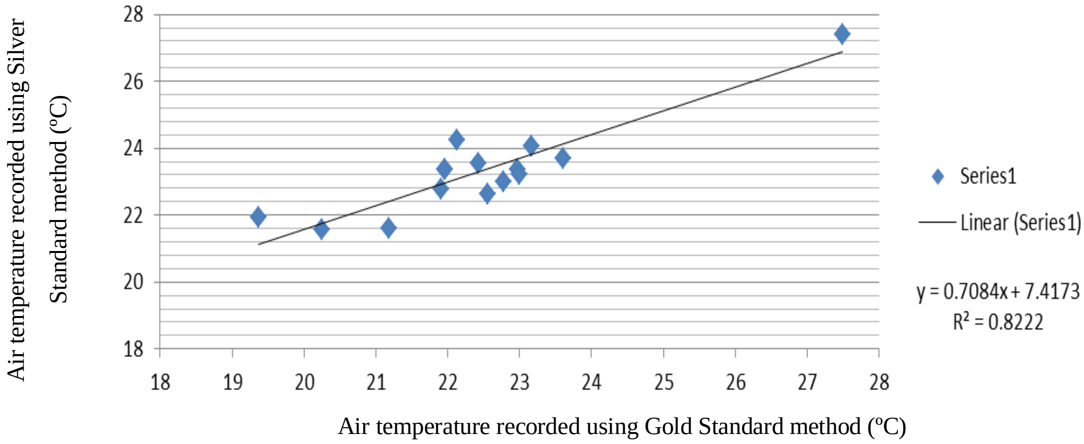

Figure 7: A regression of indoor air temperature measured using the Silver Standard method vs. indoor air temperature measured using the Gold Standard method (house no.6 data excluded).

4.2 Humidity

The second assumption made in the Silver Standard method was that humidity measured at a single height in the centre of the room will be the same as that measured using the Gold Standard method near the occupant. When comparing data from both standards (Figure 8), 75% of the data had a difference of 0-3% RH and 25% of the data had a difference of 3-6% RH. Although the correlation (R^2) value between both methods was 0.74, analysis of PMV results (reported later in the paper) indicate that these differences in relative humidity had no effect on the overall PMV, thereby suggesting that the Silver Standard method gave reasonably reliable data for PMV-PPD analysis.

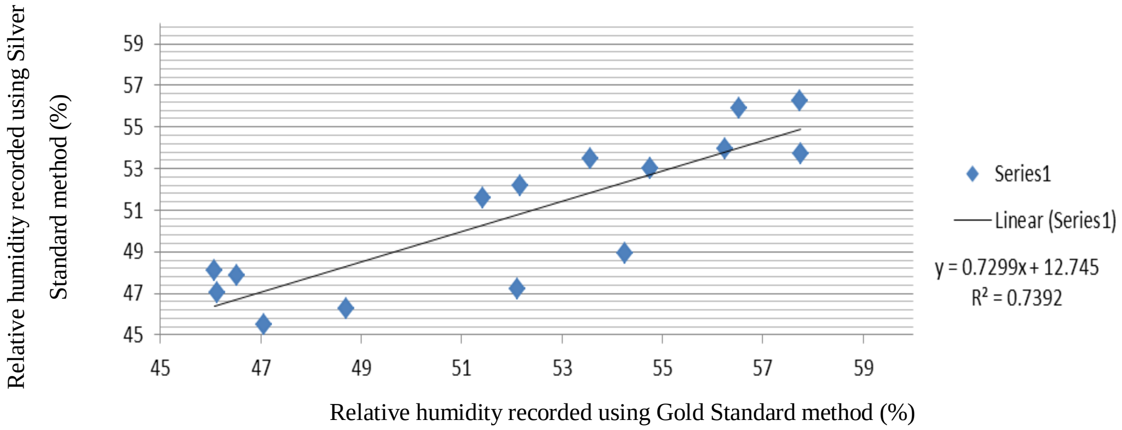

Figure 8: A regression of relative humidity measured using the Silver Standard method vs. indoor air temperature measured using the Gold Standard method.

4.3 Air Speed

Whilst using the Silver Standard method, it was assumed that the air speed would be equal to 0.1m/sec, which is the default minimum value that is used in PMV calculations and hence it would not be necessary to measure air velocity whilst conducting surveys in people's homes.

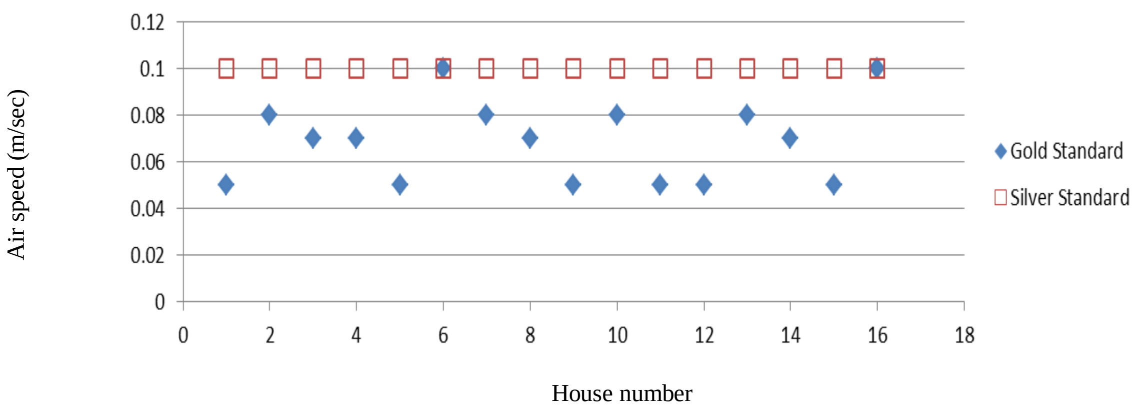

Figure 9: Air speed measurement using the Gold Standard method, compared with assumed air speed in the Silver Standard method.

Figure 9 shows that air velocity measured using the Gold Standard method was equal to or lower than 0.1m/sec. Therefore, the assumption made in the Silver Standard method, that air velocity is equal to 0.1m/sec would be satisfactory in these types of houses in the UK.

4.4 Mean Radiant Temperature

The Silver Standard method assumes that the mean radiant temperature is equal to air temperature. A comparison of mean radiant temperature measured using the Gold Standard method with air temperature measured using the Silver Standard method indicates that in 75% of the cases there was a difference of 0-1°C and in 19% of the cases there was a difference of 1-2°C.

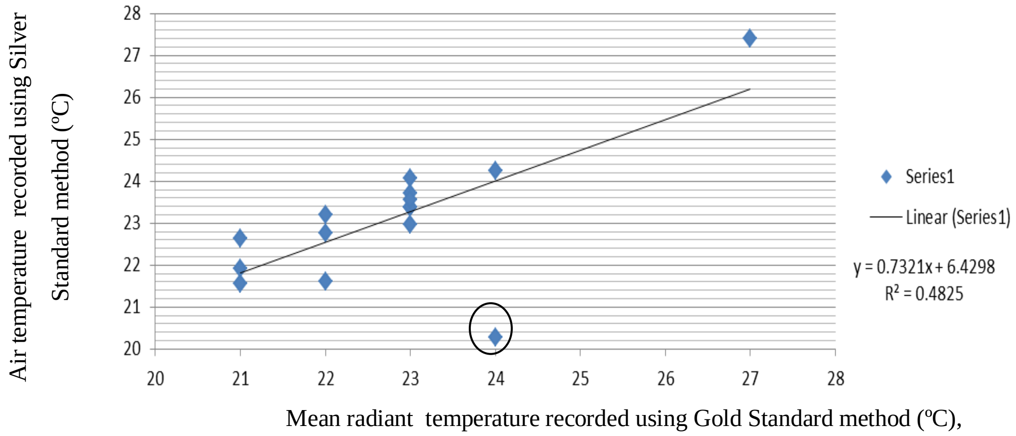

Figure 10: A regression of air temperature measured using the Silver Standard method vs. mean radiant temperature measured using the Gold Standard method (includes data from all 16 houses).

The biggest difference of 3.7°C was found in house number 6 (circled). Once again the anomaly that was found in house number 6 was as a result of the layout of the room, as discussed earlier in the analysis of air temperature. As a result of this anomaly, the comparison gave an R^2 value of 0.48. However, when house no.6 was removed from the analysis, the R^2 value increased to 0.88 (Figure 11), suggesting that it was reasonable to assume that mean radiant temperature was equal to air temperature in rooms. However, in rooms with layouts that caused an environment to be different around the occupant as compared to any other point in the room, the Silver Standard method might not be able to provide reliable/accurate data.

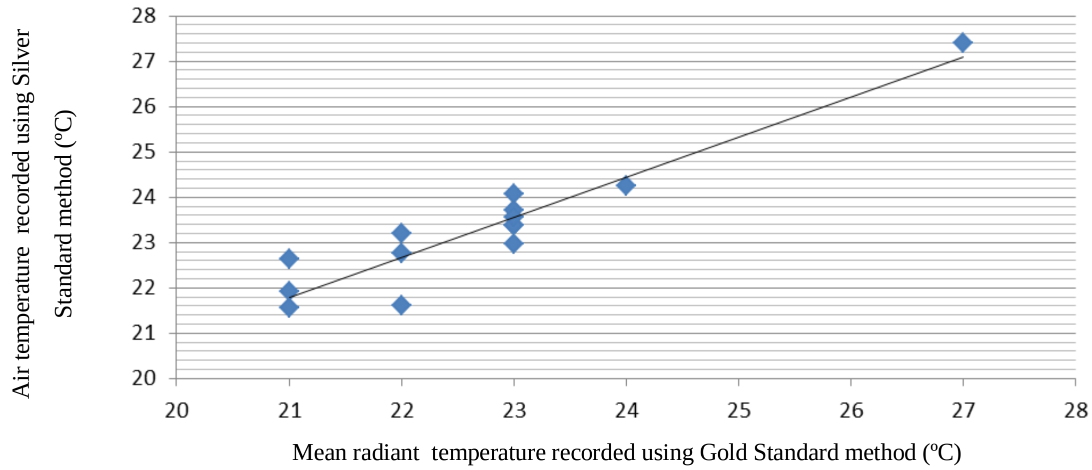

Figure 11: A regression of air temperature measured using the Silver Standard method vs. mean radiant temperature measured using the Gold Standard method (house no.6 data excluded).

4.5 CLO Value

It was assumed that the Silver Standard method that consisted of collecting self-reported data from the participants was accurate enough as compared to the data collected by the experimenter using the Gold Standard method.

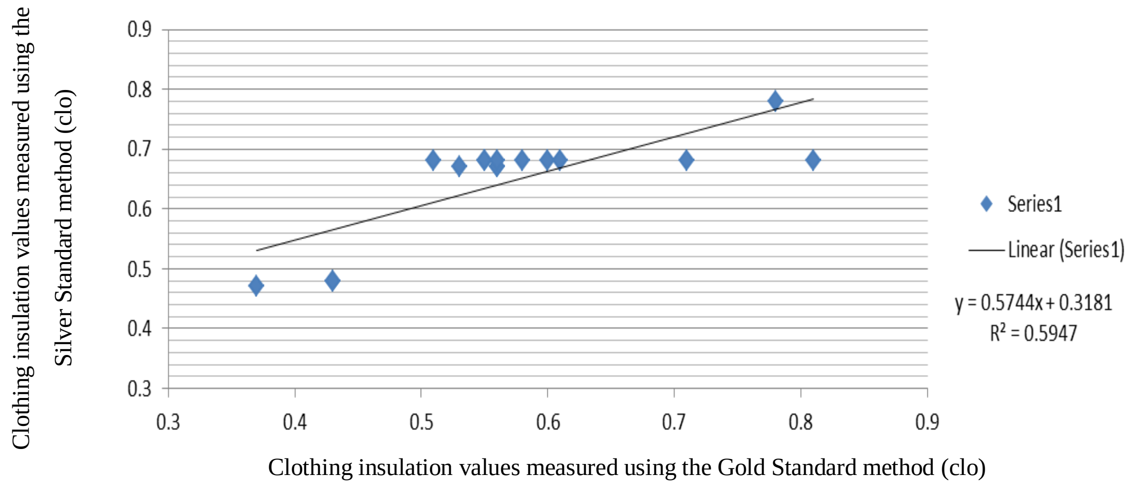

Figure 12: A regression of clothing insulation levels measured using the Silver Standard method vs. clothing insulation levels measured using the Gold Standard method.

The results show that in comparison to the Gold Standard method, the Silver Standard method overestimated the CLO values. One of the reasons assumed for the overestimation of the Silver Standard was that in the ensemble clothing list provided in the Silver Standard method, shoes were included in all scenarios and it was noticed that some of the participants were not wearing shoes. The second reason for the overestimation occurred due to the simplicity of the clothing ensemble list. The clothing ensemble list did not include different CLO values for types of socks, for example ankle socks or thick socks. Furthermore, in one house the participant was wearing traditional Indian clothing for which the CLO value was not found in the

ASHRAE or ISO Standard and hence the participants were not able to accurately report clothing insulation. Using the Gold Standard method, the experimenter obtained clo values for the Indian clothing from studies conducted by Indraganti (2010).

4.6 Predicted Mean Vote (PMV)

PMV values calculated from data obtained by both methods were compared and are shown in Figure 13. The comparison suggests that the Silver Standard method overestimated PMV values as compared to the Gold Standard method. Furthermore, a weak correlation of 0.5 was observed between the PMV values obtained from both methods.

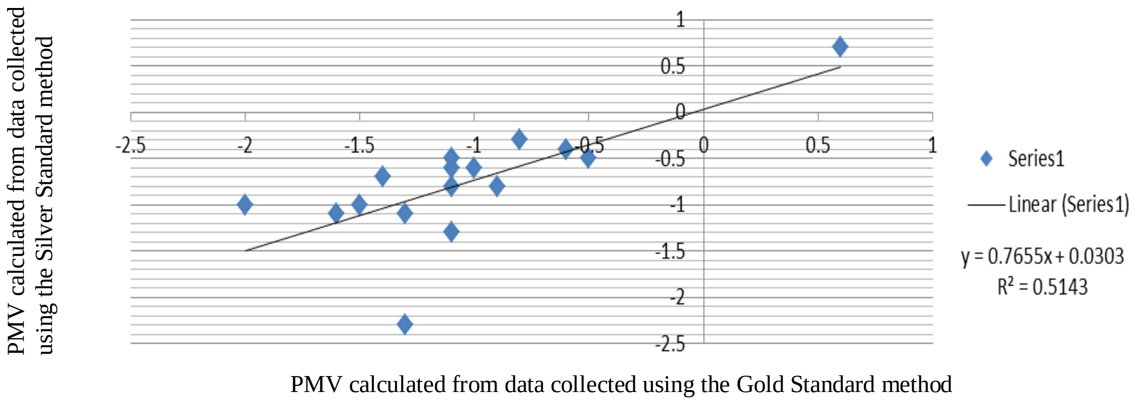

Figure 13: A regression of PMV values calculated from data collected using the Silver Standard method vs. PMV values calculated from data collected using the Gold Standard method.

In order to investigate the extent to which the six PMV variables gathered using the Silver Standard method were responsible for these differences, further analysis was carried out. For this analysis, the eight cases (samples) which had a difference of greater than 0.5 between both methods were used. PMV values were recalculated by replacing the data collected by using the Silver Standard method with the data collected by using the Gold Standard method. Table 4 below gives result of this analysis.

Table 4: Results of analysis on PMV.

Scenario	**PMV**
Average difference in PMV values calculated using Gold Standard method and Silver Standard method for the 8 cases.	0.66
Average difference for the 8 cases, values of **air temperature** measured using the Silver Standard method are replaced with values of air temperature measured using the Gold Standard method.	0.4
Average difference for 8 cases, values of **relative humidity** measured using the Silver Standard method are replaced with values of relative humidity measured using the Gold Standard method.	0.66

Average difference for 8 cases, 0.1m/sec values of **air speed** assumed in the Silver Standard method are replaced with actual values of air speed measured using the Gold Standard method.	0.66
Average difference for 8 cases, **mean radiant temperature** values (assumed to be the same as air temperature) in the Silver Standard method are replaced with actual values of mean radiant temperature measured using the Gold Standard method.	0.46
Average difference for 8 cases, values of **clothing insulation** measured using the Silver Standard method are replaced with values of clothing insulation measured using the Gold Standard method.	0.34

The results show that replacing relative humidity and air velocity had no effect on the PMV results, thereby suggesting that the assumptions made in the Silver Standard method regarding air velocity and relative humidity were reliable enough. The replacement of mean radiant temperature and air temperature took the average difference down to 0.46 and 0.4 respectively. Furthermore, the replacement of CLO values reduced the difference down to 0.34, thereby suggesting that data on CLO values should be collected using the Gold Standard method. Further analysis revealed that when Gold Standard CLO values were used, the R^2 value between both PMVs of both methods increased from 0.51 (Figure 13) to 0.81 as shown in Figure 14. The R^2 value further increased to 0.91 when data from house no.6 were removed from this analysis. This suggests that the Silver Standard method is unable to provide sufficiently reliable data on CLO values and therefore the Gold Standard method should be adopted for collecting data on clothing insulation.

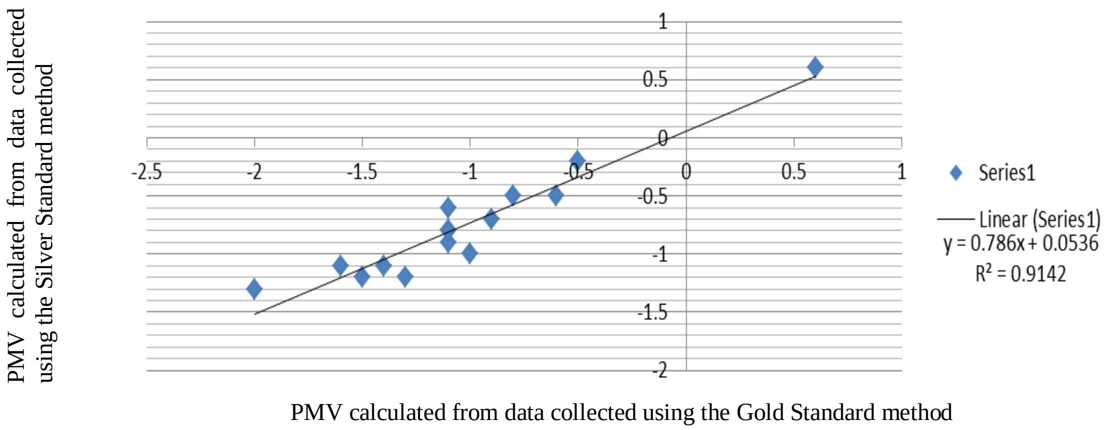

Figure 14: A regression of PMV values calculated from data collected using the Silver Standard method vs. PMV values calculated from data collected using the Gold Standard method (values of clothing insulation measured using the Silver Standard method are replaced with values of clothing insulation measured using the Gold Standard method + data of house number 6 excluded)

5. Conclusion

A comparative analysis of the data collected using the Gold Standard and Silver Standard method have been presented in this paper. The overall aim of the study was to devise a non-intrusive method to conduct thermal comfort studies in domestic environments and test its accuracy and reliability. The non-intrusive method (Silver

Standard method) was based on five assumptions that were made to simplify the data collection process, minimise disruption to householders and to avoid any intrusions on the privacy of the householders. From the analysis, the following conclusions are made:

1. If the indoor environment within the room is fairly uniform, then the air temperature data gathered using the Silver Standard method is sufficiently accurate and reliable for the estimation of thermal comfort sensation.
2. Relative humidity has little impact on PMV as compared to other variables and therefore the Silver Standard method can be used to record data on relative humidity.
3. The assumption that air velocity is less than or equal to 0.1m/second, made in the Silver Standard method, is appropriate for thermal comfort studies of the domestic buildings investigated in this study.
4. If the indoor environment within the room is fairly uniform, then the assumption that the mean radiant temperature is equal to air temperature is sufficiently acceptable.
5. The CLO value from the ensemble list that was used was not accurate enough to get the data that were required, therefore further studies should be conducted in order to develop a list which can get more accurate CLO value.
6. A good correlation (R^2 = 0.9) has been observed between PMVs obtained from the Silver Standard method and the Gold Standard method when accurate clothing insulation data were included, suggesting that the Silver Standard method has the potential to provide sufficiently reliable data for the study of thermal comfort. This method would particularly be useful in conducting large scale studies of domestic environments.

6.0 Future work

The study was conducted during the summer of 2011. Conducted as part of the MSc research project at Loughborough University, the study was limited to a sample size of 17 houses located in Loughborough. In order to further validate and refine the proposed Silver Standard method, further work is required. Firstly, it would be useful to conduct a similar study covering a larger sample in order to see whether the same results are achieved. Secondly, the Silver Standard method should also be trialled during the winter period, particularly to assess the differences between air temperature and mean radiant temperature during the heating period. And finally, further work is also required to improve the clothing ensemble list to ensure that all types of clothing are included.

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