

A field-comparison of thermal comfort with floor heating systems and air conditioning systems in Japanese homes

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Abstract

Floor heating is characterized by small horizontal and vertical temperature differences, and might be especially suitable for Japanese homes where it is customary to sit on the floor. This paper compares thermal comfort in homes while floor heating systems and air conditioning systems were in use during winter. Each dwelling had both a floor heating system and an air conditioning system, each used on alternate weeks during the survey period. Throughout the survey periods residents were asked about their current thermal sensation, thermal preference, overall comfort and foot-comfort. Air temperature, globe temperature, humidity and floor surface temperature were recorded. More than 6,000 were collected from 50 dwellings. The results showed that a floor heating system was preferred, and that it was more effective in providing a comfortable environment.

Keywords: Thermal comfort; comfort temperature; floor heating; air conditioning

1 Introduction

Floor heating is characterized by small horizontal and vertical temperature differences, and might therefore be especially suitable for Japanese homes where it is customary to sit on the floor.

Earlier research has included questionnaire surveys and climate chamber studies (Kagiya et al. 2007, Matsumae et al. 2007, Emoto et al. 2009). They found that floor heating was considered comfortable. They also found that an air conditioning heating system was found to be comfortable, and that their respondents thought the comfort level of the two systems not very different. Only university age students were used in the climate chamber study, while the questionnaire used in the survey work did not focus on the ways in which comfort might have differed between the two systems. There is in Japan a general opinion, held by residents who use floor heating systems, that they have advantages over air conditioning systems. Further exploration of the question therefore seemed to be desirable.

We first conducted a web-survey on 7th and 8th of February 2011. It has been reported elsewhere (Rijal & Omori 2011, Rijal et al. 2012), so only a brief account is given here. Respondents were asked to stay in the heated living room for an hour or more before they filled in an on-line questionnaire. The questions asked about, among other matters, whole-body thermal sensation and thermal preference, and also asked about the warmth and comfort of the feet. All respondents were over 20 years old. Residents measured the room temperature themselves at the height of 1.0m above the floor in the central part of the room. Generally the air conditioning was by forced warm air, and not always with humidity control. The total number of collected questionnaires was 1,030 (515 dwellings with each type of heating

system). This cross-sectional survey showed a clear preference for floor heating systems, and so it was decided to conduct further extended surveys to be accompanied by more complete and reliable measurements of the thermal environment (Rijal & Omori 2013). The purpose was to see whether these new data would confirm the preference for floor heating found in the web-survey, and if so to explain it.

2 Investigation method

2.1 Questionnaires

The questionnaires were based on the one we had developed for the web-survey, but including additional questions about humidity and overall satisfaction. The questionnaire aimed to extract any differences in thermal comfort there might be between the floor heating and air conditioning systems (Tables 1, 2 and 3).

The ASHRAE scale has been widely used, but the words “warm” or “cool” imply comfort in Japanese. The Society of Heating, Air-Conditioning and Sanitary Engineers of Japan (SHASE) therefore developed a modified form of the ASHRAE scale for Japan (Okuma et. al. 2008). To avoid possible misunderstanding of “neutral” in the thermal sensation scale, it is explained as “neutral (neither cold nor hot)” or “neutral (neither cool nor warm)”. We used both the ASHRAE scale and the SHASE scale.

Table 1. Questionnaires for thermal comfort and humidity

No.	SHASE scale Now, how do you feel the air temperature on whole body / floor temperature on feet?	ASHRAE scale Now, how do you feel the air temperature on whole body / floor temperature on feet?	Thermal preference Now, how do you prefer the air temperature on whole body / floor temperature on feet?	Humidity feeling Now, how do you feel the humidity?	Humidity preference Now, how do you prefer the humidity?
1	Very cold	Cold	Much warmer	Very dry	Much more humid
2	Cold	Cool	A bit warmer	Dry	A bit more humid
3	Slightly cold	Slightly cool	No change	Slightly dry	No change
4	Neutral (neither cold nor hot)	Neutral (neither cool nor warm)	A bit cooler	Neutral (Neither dry nor humid)	A bit drier
5	Slightly hot	Slightly warm	Much cooler	Slightly humid	Much drier
6	Hot	Warm		Humid	
7	Very hot	Hot		Very humid	

Table 2. Questionnaires for air movement and noise.

No.	Air movement feeling Now, how do you feel the air movement?	Air movement preference Now, how do you prefer the air movement?	Noise feeling Now, how do you feel the system operation noise?	Noise preference Now, how do you prefer the system operation noise?
1	Very low air movement	No change	Very quiet	No change
2	Low air movement	A bit less air movement	Quiet	A bit quieter
3	Slightly low air movement	Much less air movement	Slightly quiet	Much quieter
4	Slightly high air movement		Slightly noisy	
5	High air movement		Noisy	
6	Very high air movement		Very noisy	

Table 3. Questionnaires for overall comfort and satisfaction.

No.	Overall comfort By considering the thermal environment (air temp., humidity, air movement and others), please give the overall comfort now.	Satisfaction Now, please give the satisfaction of thermal environment (air temp., humidity, air movement and others).
1	Very comfortable	Very satisfied
2	Comfortable	Satisfied
3	Slightly comfortable	Slightly satisfied
4	Slightly uncomfortable	Slightly unsatisfied
5	Uncomfortable	Unsatisfied
6	Very uncomfortable	Very unsatisfied

Table 4. Description of the investigated buildings.

Building name	Constructed year	Number of houses	Number of investigated houses	
			First period	Second period
A	2006	1036	25	20
B	2003	989	-	5

The investigation was conducted in the living rooms of 50 apartment houses of two reinforced concrete buildings (Table 4) in Tokyo for two periods each of two-weeks, January 30th to February 12th (first period) and February 15th to 28th (second period)). In each two-week period, we investigated 25 households, using floor heating for one week and air conditioning for the other. The chosen dwellings had both system-types installed. To give a similar variation in outdoor temperature within a group, 12 houses used floor heating and 13 houses used air conditioning in first week, and vice versa in second week. These procedures were repeated in the second two-week period. The air temperature, globe temperature and relative humidity were measured at the height of 0.6 m above the floor in the central part of the living room (Fig. 1). Floor temperature was measured at the centre of the living room by sticking a sensor to the floor surface with surgical tape (Fig. 1). The data were recorded automatically at 10-minute intervals. Meteorological data was obtained from the nearest meteorological station.

Fifty men and fifty women (husbands and wives) took part in the surveys. They gave their responses several times in a day, and we have collected more than 6000 completed questionnaires. Sometimes residents used other heating equipment in addition to the floor heating or the air conditioning heating. We have analysed only the data where no additional equipment was in use.

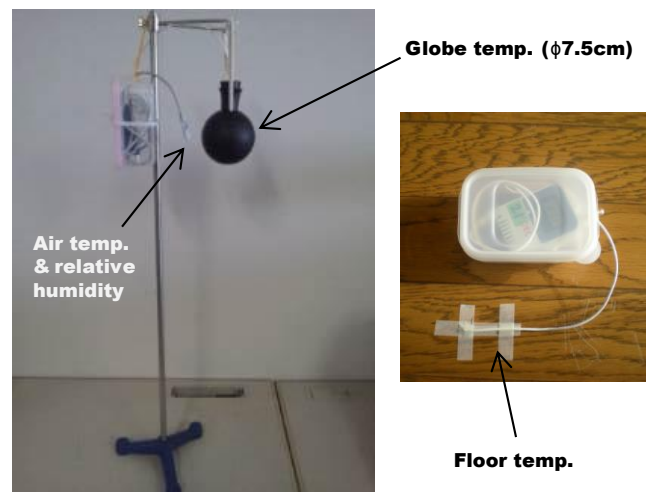


Fig. 1 Details of the thermal measurement

3 Results and Discussion

3.1 Temperature

Outdoor Air temperatures:

The mean outdoor air temperature for the floor heating mode was 5.7 °C and the relative humidity 49%. For the air conditioning mode they were 5.9 °C and 47%. The outdoor temperature and humidity can therefore be considered to be the same for both heating modes.

Indoor temperatures:

The distribution of indoor air temperature, globe temperature and floor temperature are shown in Figs. 2 & 3. The mean indoor air temperature and its standard deviations for the two types of heating were virtually identical in the two modes of operation. The same is true of the globe temperatures. The indoor temperatures can therefore be regarded as the same for both modes. The mean floor temperature for the floor heating mode was 4.7 °C higher than for the air conditioning mode (Fig. 3(b)).

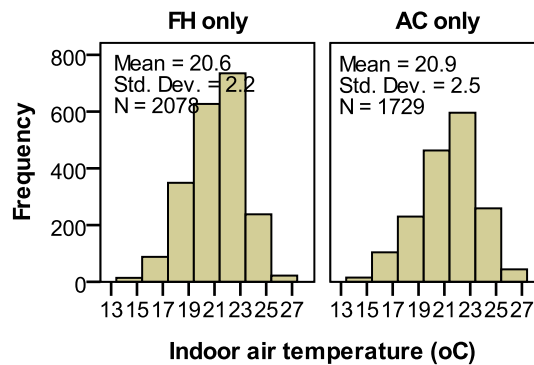


Fig. 2 Distribution of air temperature at the time of voting.

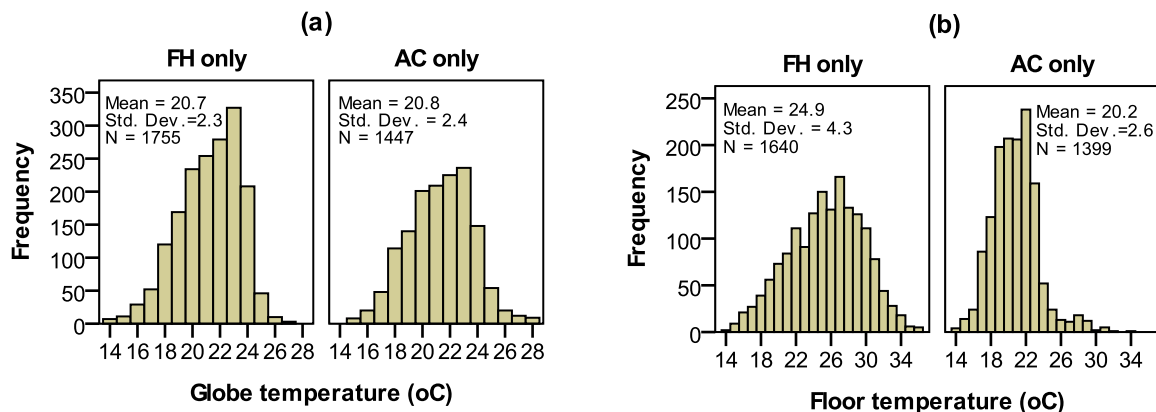


Fig. 3 Distribution of globe temperature and floor temperature at the time of voting.

3.2 Evaluation of thermal sensation of the whole body

From the web survey, which had a large arguably random sample of people, we had concluded that the SHASE scale was better than the ASHRAE scale, having more uniform psychological widths of its scale-categories, and its ‘neutral’ category being close in meaning to the ‘prefer no change’ category on the thermal preference scale. We have therefore chosen it for the analysis of the present data.

The Fig. 4(a) compares the distribution of the thermal sensation on the SHASE scale for the two modes, with the 95% confidence intervals of the percentages shown. The mean thermal sensation of the SHASE scale for floor heating is 0.1 higher than the air conditioning – a very small difference. However, the proportion responding “4 neutral” for the floor heating mode is higher than for the air conditioning mode. The proportion responding “3 slightly cold” for floor heating is also lower than for the air conditioning.

A very similar picture is evident from the question about thermal preferences (Fig. 4(b)). With floor heating more people say they desire no change in their warmth sensation, and fewer say they would prefer to be warmer. The results showed that the residents who used floor heating felt slightly more thermally comfortable in the whole body compared with the residents who used air conditioning.

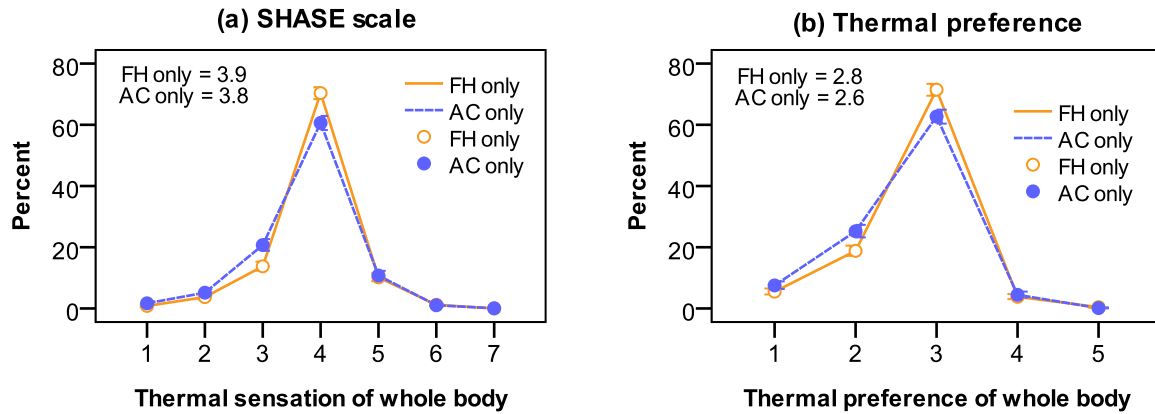


Fig. 4 Comparison of thermal sensation and thermal preference for the two modes

3.3 Evaluation of the thermal sensation of the feet

Fig. 5(a) shows the distribution of the thermal sensation of the feet, with the 95% confidence intervals of the percentages. The mean thermal sensation of the SHASE scale for floor heating is about 1 scale unit warmer than the air conditioning – a substantial difference. The proportion of “4 neutral” for floor heating is much higher than the air conditioning, while the proportion of “3 slightly cold” for floor heating is much lower than with the air conditioning. The residents were less likely to have cold feet with the floor heating. Despite the similarity in the overall subjective warmth for the two modes, as shown in Fig. 5(a), there was a large difference in the thermal sensation of the feet.

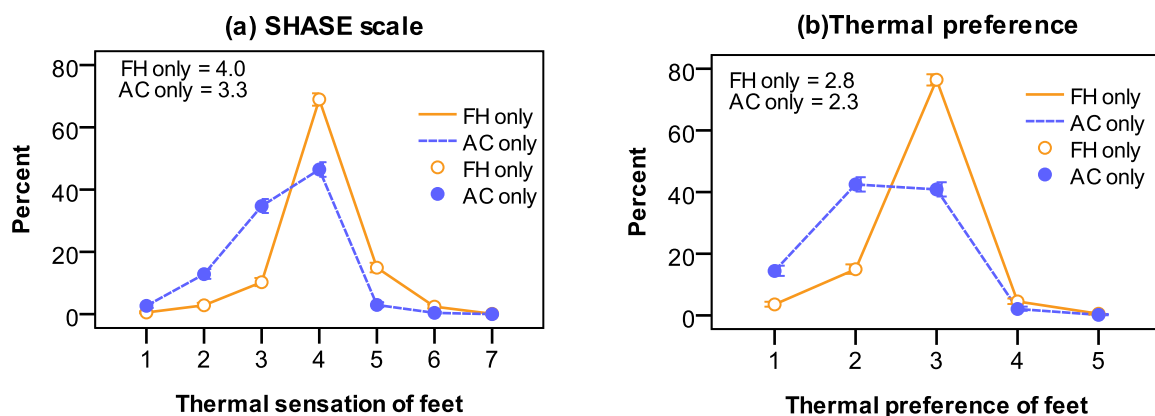


Fig. 5 Distribution of thermal sensation and thermal preference for the feet.

It may be wondered whether people liked their feet to be warm. That this was so can be found from the distribution of thermal preference for the feet. The mean thermal preference for the feet is half a scale unit higher with floor heating – a considerable advantage. The improvement is statistically significant ($t=24.4$, $p<0.001$). The proportion who desired no change in the thermal sensation of the feet was very much higher with the floor heating (Fig. 5(b), while far fewer would prefer their feet to be warmer. The floor heating reduced the incidence of people wanting their feet to be warmer without much increasing the few who wanted their feet to be cooler. So the feet were much more comfortable with floor heating.

3.4 Evaluation of humidity

Although the actual indoor humidity was virtually the same for the two types of system, the homes using floor heating were perceived to be rather more humid than those using AC. The distribution is shown in Fig. 6(a) (the ‘humidity feeling’). That they preferred this condition is revealed by the humidity preference distribution (Fig. 6(b)). Many more people were pleased with the humidity with the floor heating.

It is well known that subjective perceptions of humidity do not map well onto actual humidities. People are not equipped with humidity sensors, so the perceived humidity is a mental construct, and may be but slightly to humidity as a physical measurement. So the subjective humidity relates to something other than the measured humidity of the environment, perhaps to the amount of airborne dust, which can produce irritation in the eyes and throat be interpreted as ‘dryness’. Whatever the reason may be, our respondents preferred the ‘humidity’ in the rooms with floor heating. The meaning of subjective humidity requires further research.

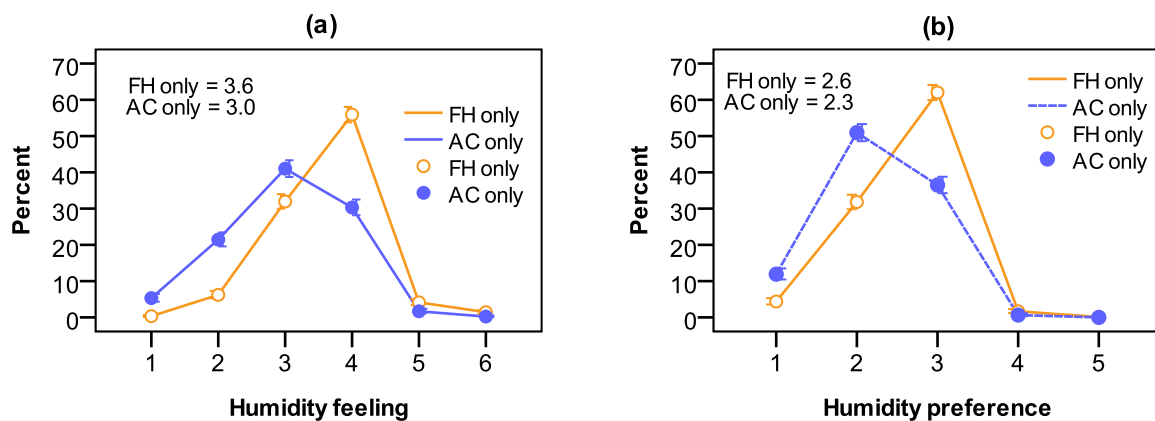


Fig. 6 Assessments of humidity

3.5 Evaluation of air movement

The air movement was evaluated for the floor heating and for the air conditioning modes. An air-conditioning system is fan-driven, and this is likely to increase to some extent the air movement within the room. Air speed was not measured, but our respondents perceived the air movement to be greater in the AC mode. Fig. 7(a) shows the distributions of the air movement sensations, with the 95% confidence intervals of the percentages.

The mean air movement feeling for floor heating was about 1.6 scale units less – a very large difference ($t=49.2$, $p<0.001$). Notably the proportion who felt no air movement (“1 not felt”) was very much higher for floor heating than with air conditioning.

But did they like the absence of a sense of air movement? The mean air movement preference for floor heating and air conditioning were significantly different ($t=31.6$, $p<0.001$). The proportion who desired no change in their sensation of air movement (“1 no change”) for the floor heating mode is far higher than the air conditioning (Fig. 7(b)). Nearly everyone with floor heating liked the lack of perceived air movement, wanting no change, while this percentage fell to some 60% in the AC mode.

The results show that floor heating was preferred to the air conditioning from a viewpoint of perceived air movement.

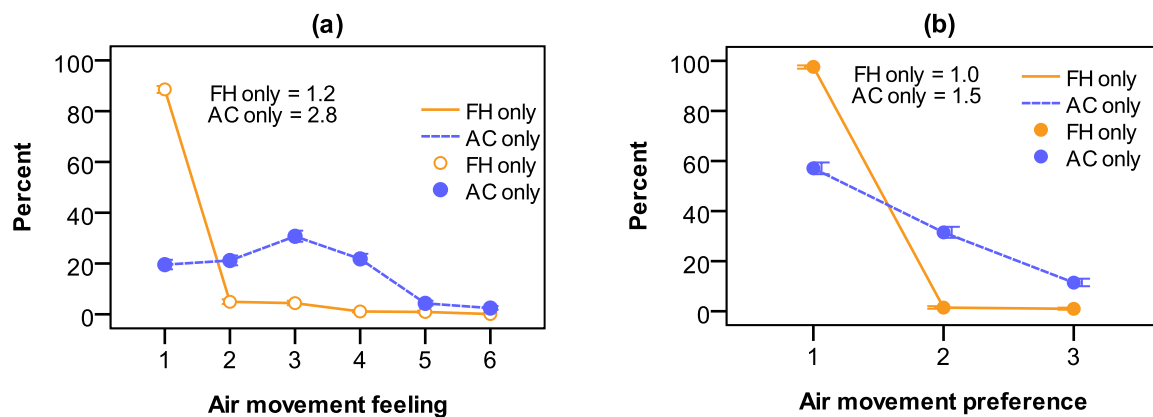


Fig. 7 Distribution of perceived air movement and air-movement preference.

3.6 Evaluation of system noise

A floor heating system is silent, while an AC system has some noise from the fans in the ducting. The difference proved very noticeable to the occupants, as can be seen at once from Fig. 8(a). The preference scale shows that 50% of those in AC rooms would have liked it ‘a bit quieter’ or ‘much quieter’. In the floor heating mode everyone was content with the lack of noise, 100% desiring ‘no change’ (Fig. 8(b)).

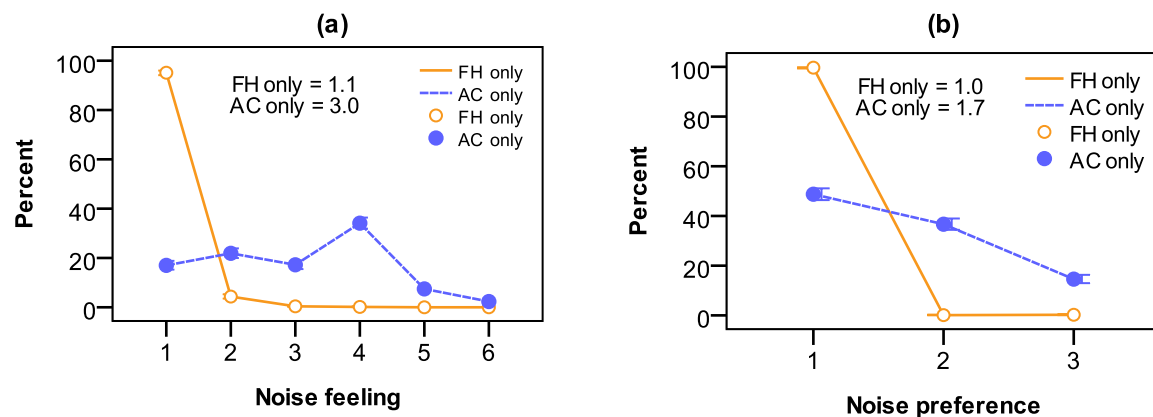


Fig. 8 Evaluation of system-noise

3.7 Evaluation of overall comfort and satisfaction

The overall comfort of residents was evaluated. Fig. 9 shows the distribution of overall comfort for the two modes, together with the 95% confidence intervals of the percentages. The mean overall comfort of the floor heating mode was substantially higher than for the AC mode (3.1 compared with 2.6). The difference statistically significant ($t=18.0$, $p<0.001$). The proportion responding “2 comfortable” was considerably higher with floor heating than with air conditioning. This agrees with the result of the question about how satisfied they were (Fig. 10). The clear advantage was with the floor heating systems.

The results showed that the thermal satisfaction of the floor heating was higher than with the air conditioning.

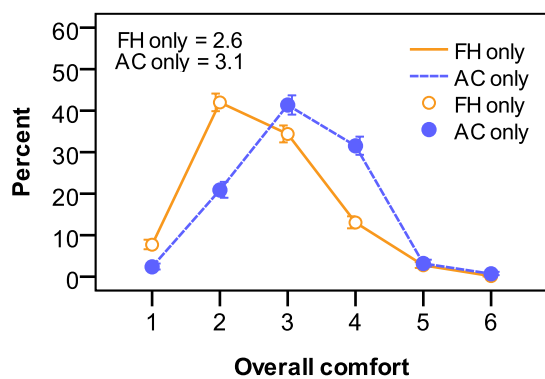


Fig. 9 Comparison of overall comfort

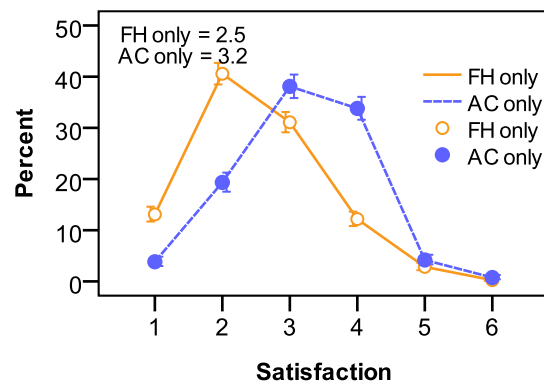


Fig. 10 Comparison of satisfaction

4 Conclusions

The measurements of the thermal environment demonstrated that the two modes did not differ appreciably in their indoor and outdoor temperatures during the periods of the survey, except of course that the floor was warmer with floor heating. The virtual equality of indoor and outdoor temperature in the two modes enabled us to directly compare the subjective responses for the two modes.

There was no practical difference in the overall sensation of warmth between the two modes, the floor heating and the air conditioning being perceived at equally warm. However, the more detailed questions all revealed a preference for the floor heating mode, confirming the finding of our earlier web survey.

With floor heating fewer people desired any change in their overall sensation of warmth. Their feet were warmer, and this they welcomed. They assessed the space as more humid, and they preferred it to be so, though the reason for the different assessment is uncertain. They perceived less air movement in the floor heating mode, and this they preferred. They liked the lack of noise with floor heating. Finally they rated themselves as more comfortable and more satisfied overall.

The subjective advantage of floor heating compared with AC for winter heating for this sample of people in the living room of their dwellings is therefore clearly revealed.

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