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A field study to validate the positive effects of individual control on thermal comfort in residential buildings

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Abstract

Although the adaptive comfort model has gained unprecedented popularization during the past few decades, the mechanism behind the model, especially with regard to certain key hypotheses, still requires further clarification. To validate whether people with greater individual control tend to attain comfort state in wider ranges of indoor thermal environments, we designed an investigational study in Beijing apartments with different degrees of individual control over space heating systems. The statistical results show that occupants with individual control had lower neutral temperature during the winter time and expressed more positive comfort-related perceptions than those without capability of personal control. Furthermore, the mechanism of the positive impact of individual control was discussed in terms of adaptive processes and economic factors. The results show that individual control over space heating systems was helpful to ensure residents make their own trade-off between thermal comfort and heating fees. These findings can provide support for the adaptive model and can also serve as a reference for decision makers and designers when they choose appropriate residential space heating systems with concerns about residents' demand and conserving energy.

Keywords: adaptive thermal comfort, individual control, neutral temperature, residential space heating, economic factors

Nomenclature

T_a	Indoor air temperature (°C)
T_{op}	Operative temperature (°C)
RH	Relative humidity (%)
ν	Air velocity (m/s)
MET	Metabolic rate
CLO	Clothing insulation (clo)

1 Background

During the past few decades, the adaptive comfort approach has gained unprecedented popularization due to increasing concerns about building environment improvement and the consequential need to enhance building energy efficiency (de Dear et al, 2013). Since the re-emergence of adaptive comfort approach, results of many field studies have given support to the fundamentally different but not new model (for instance, Karyono et al, 2002; Fato et al, 2004; Cao et al, 2011). Through numerous researchers' unremitting efforts, especially Brager and de Dear (1998; 2002) and Nicol and Humphreys (1998; 2002), the legitimacy of the adaptive comfort model has been recognized by recent comfort standards such as ASHRAE Standard 55 (2013), EN 15251 (2007) and even some national standards like Chinese GB/T 50785 (2012).

Compared with Fanger's Predicted Mean Vote and Predicted Percentage Dissatisfied (PMV-PPD) model (Fanger, 1970), which predicts human subjective sensation based on steady-state heat balance calculation of human body, the adaptive approach emphasized the role occupants play in attaining their own thermal comfort (de Dear and Brager, 1998). According to the adaptive hypothesis, the discrepancies between PMV and the observed comfort sensation in real buildings can be attributed to three adaptive processes: physiological acclimatization, behavioral adjustment (clothing, windows) and psychological habitation or expectation. To increase the rigor of the adaptive model and extend its application scope, many thermal comfort studies have been conducted in different contexts to offer support for the theory. For instance, de Dear (1998) and Nicol et al (2010) collected quality-ensured database from field investigations to derive the comfort equations in ASHRAE Standard and European standards EN 15251 respectively. Schweiker et al. (2012) developed and validated an experimental methodology to quantify the individual contributions of the three mentioned adaptive processes in warm indoor environments. To verify the effects of physiological acclimatization on human thermal adaptation, Yu et al (2012) demonstrated in climate chamber experiments that subjects who were acclimated to naturally ventilated environments had a significantly stronger capacity for physiological thermoregulation than those who were acclimated to air-conditioned environments. Yao et al (2009) developed a modified PMV model to reflect adaptive factors such as culture, climate, psychological and behavioral adjustments by proposing an adaptive coefficient. And concluded that their model could be a contribution as a bridge between lab-based PMV model and the adaptive comfort model.

However, despite great progresses have been made, there still exist some controversial hypothesizes in adaptive comfort model remain largely unresolved. Among all those controversies, one important hypothesis stated in this way: occupants in free-running buildings can achieve thermal comfort in a wider range of indoor temperatures compared to occupants in centrally controlled air-conditioning buildings because of the increased levels of personal control afforded by approaches like operable windows (de Dear and Brager, 1998). The main issue of this hypothesis is that whether different degrees of individual control can influence occupants comfort perception. Some researches doubted that the expectation hypothesis has not been confirmed by experimental or survey data, and its underlying premises and logic need rethinking and a more solid foundation (Halawa, 2012). To examine the relationships between individual control and occupants comfort perception, many comparative experiments were designed and conducted. Brager et al (2004) carried out a field study in a naturally ventilated office building, and found that occupants with more opportunities to operate windows reported temperatures closer to neutral than those who had less capability to control the windows, even though both groups were exposed to very similar thermal environments. Goto et al (2007) conducted a similar longitudinal study in six Japanese buildings, but they reported no considerable differences in occupants' thermal perception in the two groups of buildings. Zhang et al (2010; 2013) conducted field investigations in a hot and humid climate, and found that occupants in naturally ventilated buildings reported lower neutral temperatures than those in air-conditioned buildings. A more recent 'right here right now' chamber experimental study designed by Zhou et al (2013) reported that occupants' anticipated control decreased their thermal sensation vote (TSV) by 0.4-0.5 and improved their thermal comfort vote (TCV) by 0.3-0.4 in neutral-warm environment.

In addition to the consequential need to offer more solid support for the adaptive comfort theory, Chinese comfort researchers are also confronted with a more urgent and practical issue: centralized space heating and individual space heating, which one is more appropriate for residential buildings in China? Since the 1950s, most urban residential buildings in northern China have been equipped with district heating supply facilities having uncontrollable terminals, while most residents in southern China tended to heat their apartments individually. The 2010 National Statistical Yearbook shows that the district heating supplied buildings increased from 2.66 to 3.56 billion m^2, with an average annual growth of 0.3 billion m^2 (Ding et al 2011). Despite miscellaneous problems with district heating supply in the northern heating region, more and more people from southern region, especially the hot summer and cold winter zone, have been requesting district heating supply in residential buildings in order to improve living standards. Recently, a debate has arisen focusing on the issue mentioned above. Although this is a complicated problem involving aspects like energy structure, system design, economic factors, et al, it is noteworthy to mention a significant distinction between these two space heating systems in China: individual system allows users to adjust internal thermal conditions whenever they want, but centralized system users had little or no control capability over their immediate indoor climate. Therefore, it is meaningful to compare these two space heating systems from perspectives of indoor thermal environment, thermal comfort and heating energy consumption.

In accordance with previous researchers' contributions, we designed a field study and tried to answer the following issues: 1) how and to what extend do different degrees of personal control influence human comfort perception? 2) What benefits can we obtain if residents were offered with terminal controllable heating systems?

2 METHODS

2.1 Assumption

As graphically represented in Figure 1, if we assume the adaptive comfort model is credible, then the following results can be derived. Occupants with higher degrees of individual control could obtain more neutral thermal perception and more positive comfort related assessments. Therefore, if we design an investigation including two subject groups with different degrees of individual control, the results can be used to validate or challenge the basic hypothesis in adaptive comfort theory.

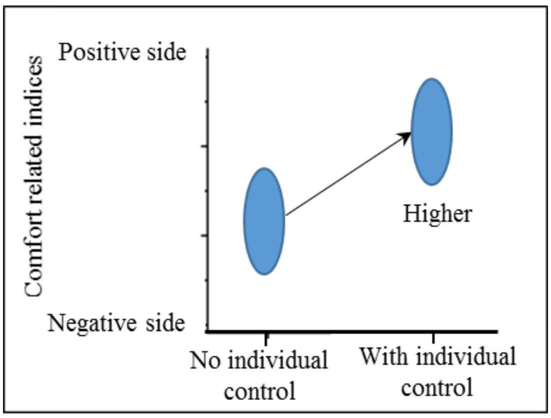

Figure 1 Graphical representation of the hypothesis

2.2 Investigation design and subjects selection

After extensive searches, we selected a residential community with two typical kinds of space heating systems in Beijing, North China (39°54'N, 116°25'E). Beijing is a typical city in the cold climate zone: the summer is warm, and the winter is cold and dry. The mean outdoor air temperature is 26.5°C in July and -3.8°C in January. The relative humidity is around 70% in summer and 42% in winter.

To recruit apartments with different degrees of individual control over space heating system, we chose 118 apartments in the target community to do this field investigation. As shown in Table 1, all these case apartments were divided into two groups. Group BJ-A were equipped with terminal uncontrollable district heating supply facilities. Occupants in this group had no direct way to control the indoor thermal environment. Group BJ-B were heated by individual space heating systems. Occupants in this group were able to control the indoor thermal environment by adjusting the set points of space heating systems. As most of these apartments were located in one community, other factors such as the presence of operable windows, the age of the building, and the spatial layout could be ensured to be similar in the initial background survey. Furthermore, no significant differences existed among subjects in terms of other characteristics such as age, gender, and annual income.

Table 1 Summary of the surveyed buildings

	Time	Number of apartments	Space heating system	Individual control
BJ-A	Dec. 2012 ~ Feb. 2013	Background level: 45 Detailed level: 15	District heating supply	No
BJ-B	Dec. 2012 ~ Feb. 2013	Background level: 41 Detailed level: 17	Individual household gas boiler heating	Free to adjust

2.3 Investigation content

To ensure the reliability of investigation results, we designed the study into two levels (as shown in Table 2). The detailed level aimed to record the indoor thermal conditions, occupants' perceived thermal comfort, and heating energy consumption in minute detail, while the goal of the background level was to extend the scope of the research and verify the results of the detailed level investigation. The apartments in the detailed study were observed continuously, and those in the background investigation were examined only once.

Table 2 Two investigation levels

Investigation level	Measurements
Background study	T_a, T_g, and RH
Detailed study	T_a, T_g, v, RH, and meteorological station

As for the investigation contents, both simultaneous measurements of physical parameters and subjective questionnaires were included in our methodology. Indoor thermal parameters were continuously measured at 5-minute intervals with different instruments; the valid ranges and accuracies of the monitoring instruments are listed in Table 3. In each surveyed apartment, sensors with self-recording loggers were placed about 1.0 meters above the floor in the living room, bedroom, and reading room.

Table 3 Accuracy of environmental monitoring instruments

Parameter	Valid range	Accuracy
T_a (ºC)	5~35	±0.2
RH (%)	20~80	±3
ν (m/s)	0~3	±5%
T_g (ºC)	5~50	±0.2

Occupants' subjective sensations were determined by questionnaires including thermal sensation vote (TSV), thermal comfort vote (TCV), thermal preferences, thermal acceptance, etc. As shown in Table 4, the TSV adopted a seven-point scale ranging from cold (-3) to hot (+3), with neutral (0) in the middle. Thermal preferences were assessed using a three-point scale: 'warmer', 'no change', and 'cooler'. Clothing insulation was calculated in accordance with ISO 9920 (2009). In total, 657 valid questionnaires and corresponding indoor thermal conditions were collected.

Table 4 Thermal comfort index and its scale

Scale	TSV	TCV	Thermal acceptance	Thermal preference
3	Hot	--	--	--
2	Warm	--	--	--
1	Slightly warm	--	Very acceptable	Warmer
0	Neutral	Comfortable	Just acceptable or Just unacceptable	No change
-1	Slightly cool	Slightly uncomfortable	Very unacceptable	Cooler
-2	Cool	Uncomfortable	--	--
-3	Cold	Very uncomfortable	--	--

Additionally, in order to collect space heating energy consumption data of apartments in group BJ-B, we recorded their gas meter's readings before and after the detailed investigation. In this way, space heating gas consumption could be roughly calculated. To valid this results, we also collected heating gas consumption records in the background investigation.

3 RESULTS

3.1 Indoor thermal environment corresponding to questionnaires

Indoor thermal climates experienced by occupants tend to affect their thermal perception directly. Before we look into occupants' thermal response of these two groups, we would like to present the indoor thermal conditions corresponding to subjective questionnaires. As shown in Table 1, we divided the surveyed apartments into two groups according to degrees of individual control. Group BJ-A had no individual control over the indoor thermal climate, while the space heating systems in group BJ-B were terminal adjustable.

Figure 2 shows the distributions of indoor thermal parameters of group BJ-A and group BJ-B. The T_a mainly fell between 18℃ and 24℃, and RH ranged from 20% to 50% in most cases. The conditions of low indoor temperature could also be observed in both groups. Compared with BJ-B apartments in some cases, BJ-A apartments might have higher T_{op}, but the proportion of these cases is quite small. To test whether there exist significant difference in comfort-related physical parameters between these two groups, Table 5 shows the independent sample test results (t-test). It can be seen that no significant difference in comfort-related parameters existed between group BJ-A and BJ-B, which means the occupants in these two groups experienced similar thermal environments when they were answering the questionnaires.

Table 5 Comfort-related thermal parameters (significance of difference is labeled 'strong' or 'no' for p-values < 0.05 in an independent samples t-test)

Parameters	BJ-A			BJ-B			Significance of difference
	Max	Ave	Min	Max	Ave	Min	
CLO	1.48	0.86	0.35	1.51	0.87	0.41	no
MET	1.4	1.2	1.0	1.5	1.2	1.0	no
T_{op}	28.4	21.5	14.6	25.3	21.3	14.3	no
v	0.56	0.02	0.00	0.28	0.02	0.00	no
RH	61.5	34.4	11.7	68	36.9	10.6	no

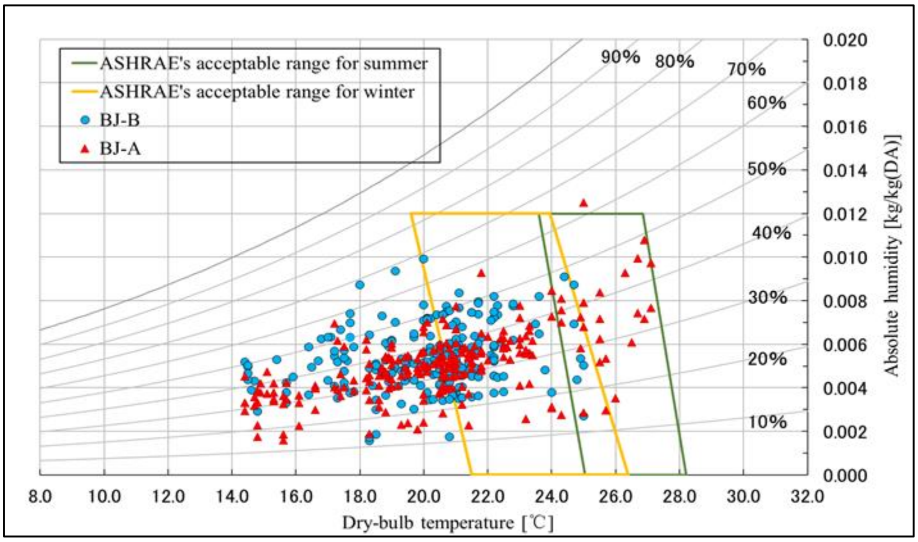

Figure 2 Distribution of indoor thermal parameters

3.2 Thermal comfort

To quantitatively describe occupants' subjective thermal perception, various comfort related indices (e.g. TSV, TCV, PMV, etc.) were proposed and relationships among these indices have been explored through large amount of well-designed experiments (Fanger, 1970). Through these indices, occupants could express their subjective opinions about whether indoor thermal conditions fulfilled their demands or not. If they were satisfied, they were supposed to vote a positive evaluation; otherwise, they could indicate their dissatisfied sensation by voting a negative value.

Figure 3 compares occupants' thermal perception from perspectives of TSV, thermal preference, thermal acceptance and TCV. Figure 3.a shows that occupants' TSV in both groups were broadly distributed, but were mainly concentrated among the 'neutral' and 'slightly cool or warm' options. Compared with group BJ-A, higher percentage of occupants in BJ-B apartments vote 'neutral' sensation. Figure 3.b indicate that majority of occupants in both groups want to maintain their current indoor thermal conditions. However, group BJ-B had higher percentage of occupants choose 'no change' option. Figure 3.c shows occupants thermal acceptance options. Although both groups had the overwhelming majority (over 80%) of respondents that could accept their current thermal conditions, occupants in group BJ-B expressed higher acceptance percentage. Figure 3.d shows statistical distributions of TCV. It can be seen that group BJ-B had higher average comfort vote value.

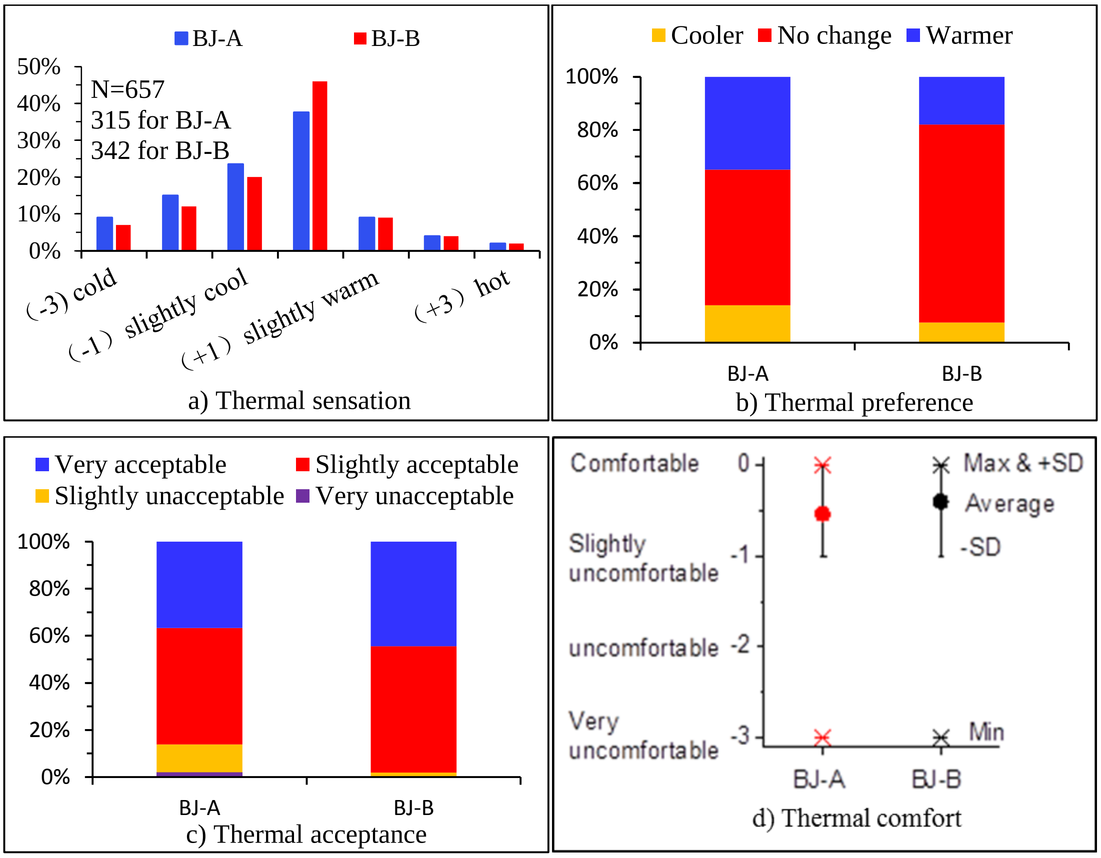

Figure 3 General comfort evaluation

To describe occupants' thermal response with the change of indoor temperature, Figure 4 examines the relationships between occupants' subjective thermal sensations and physical thermal indices. The linear regression fitting results for the divided two groups are illustrated in Figure 4. During the process of linear fitting, the weights of the valid vote numbers in each index bin were considered. The final regression models contained T_{op} (as the thermal environment index) and the mean TSV in each T_{op} bin; R^2 was regarded as an index of fitting accuracy. The results show that each group's sensitivity (slope of the regression line) of TSV to T_{op} varied considerably, indicating substantial differences in occupants' thermal responses. The slope of the regression line indicates that occupants in BJ-B apartments were less sensitive to variation of T_a, and therefore reported more neutral thermal sensation. With the ideal thermal environment defined as the neutral state, the neutral T_{op} was determined by solving regression equations with

TSV=0. In this way, the neutral T_{op} values for groups BJ-A and BJ-B were calculated as 20.7°C and 18.1°C respectively.

If we further compare Figure 3 and Figure 4 with Figure 1, it seems that the field investigation results support the hypothesis we assumed well: with higher degrees of individual control, occupants could obtain more neutral thermal perception and more positive comfort related assessments.

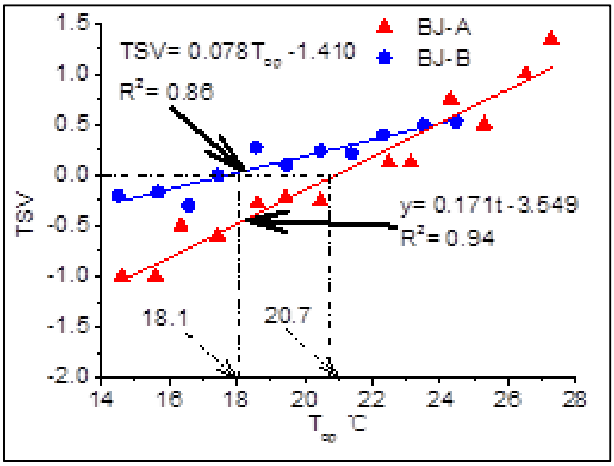

Figure 4 Linear regressions of TSV as a function of T_{op}

4 Discussion

Whether personal control can influence occupants' thermal comfort? This is an important basic hypothesis in adaptive comfort theory. Is it true? Many efforts (for instance Brager et al, 2004; Goto et al, 2007; Zhou et al, 2013) have tied to answer this question. If the hypothesis has been demonstrated to be true, then what is the mechanism behind it? And what can we learn from it? Furthermore, the results of this study support the hypothesis so well. Is there any other factors beyond individual control that can enlarge the differences between group BJ-A and BJ-B.

4.1 Individual control and thermal comfort

Can individual control ability improve human thermal comfort perception? There exist two academic opinions related to this problem. Fanger and Toftum (2002) assumed that occupants with low degrees of personal control believe it is their destiny to live in non-neutral environments, thus resulting in lower thermal comfort expectations. According to this assumption, occupants with fewer opportunities for personal control would demonstrate better thermal response when the thermal environment varied from neutral. In contrast, Nikolopoulou and Steemer (2003) supported the positive effects of individual control on perceived thermal comfort and hypothesized that people with high levels of control over the source of discomfort would be less irritated by it, thereby greatly reducing their negative emotional responses. Nikolopoulou and Steemer's opinion, which essentially states that high degrees of personal control can contribute to high thermal acceptance, is quite similar to the central notion of the adaptive comfort model. As de Dear and Brager (2002) stated:" the primary distinction between the building types was that the NV buildings had no mechanical air-conditioning, and the natural ventilation occurred through operable windows that were directly controlled by the occupants. In contrast, occupants of the HVAC buildings had little or no control over their immediate thermal environment."

To demonstrate the hypothesis that people with higher degrees of personal control tend to accept wider range of indoor thermal environment, both field studies and chamber experiments have been conducted. Table 6 lists some findings of these studies. It can be observed that occupants with higher degrees of personal control tended to report more positive comfort evaluation and have closer match of indoor neutral temperatures with outdoor climates (higher neutral temperature in warm season but lower neutral temperatures in cool season). These findings offer good support for the hypothesis in the adaptive model proposed by de Dear and Brager (2002) and Nicol and Humphreys (2002).

AS for the question why higher degrees of individual control can contribute to more comfortable perception, it may be explained in this way: occupants with more personal individual control approaches tend to have an increased ability to keep themselves in a comfortable state by removing the source of discomfort in a timely manner, thus resulting in more positive comfort related evaluation and lower motivation to change their current thermal environment.

Table 6 Evidences support the positive effects of individual control on thermal comfort

Ref.	Season conditions	Location	Building types	Degrees of personal control	Neutral temperature ^oC
Brager et al (2004)	Summer	San Francisco	Office building	Low	23(T_{op})
			Office building	High	21.5(T_{op})
Present study	Winter	Beijing	Residences	No	20.7(T_{op})
			Residences	High	18.1(T_{op})
de Dear et al (1991)	Summer	Singapore	Air conditioned	Low	24.2 (T_{op})
			Naturally ventilated	High	28.5(T_{op})
Zhou et al (2013)	Warm conditions	Beijing	Air conditioned	Low	Higher TSV
			Air conditioned	High	Lower TSV
Schweiker et al (2013)	Warm conditions	Germany	Air conditioned	Low	Higher TSV
			Air conditioned	High	Lower TSV

4.2 Factors beyond individual control: who should pay for the space heating?

Although the above analysis have tried the best to explain that the difference in the thermal comfort is mainly (if not purely) due to the difference in terms of personal control, one may still doubt: is there any other factors beyond individual control that can influence the results? Indeed, the payments of these two heating forms were different. The following section aims to analyze the effects of economic factors on occupants comfort perception and their adaptive behaviors.

From the point of view of residents, heating fee is a crucial consideration when they evaluate different heating forms. It is therefore very important to compare the cost of different heating forms. Take a 100 ㎡ house, for instance; Table 7 shows the detailed heating fee comparison. For BJ-B apartments the heating fee varied in the range of 285.9-515.6 US$/a, while BJ-A occupants had to pay 407.5~489.0 US$/a. The heating fee of BJ-B apartments were determined by the actual amount of gas they consumed, while BJ-A apartments had to pay in a one-size-fit-all mode, which means almost every BJ-A apartment should pay the same.

Table 7 Economic analysis of a 100 ㎡ house

	Beijing	
Heating form	GH	DHS
HGC, $m^3/(m^2 a)$	5.6~12.4	0
HEC, $KWh/(m^2 a)$	0	0
Natural gas price, US$/$m^3$	0.34	0
Costs for equipment, US$/a	97.8 [1]	0 [2]
Gas fee, US$/a	188.1~416.3	0
Electricity fee, US$/a	0	0
Heating fee, US$/a	285.9~515.6	407.5~489.0

As individual control approaches allow occupants in BJ-B apartments to determine internal thermal conditions and heating fees based on their own choice, the diversity of individual heating demands in such apartments emerged. Figure 5 shows the internal temperature distribution of detail investigated BJ-B apartments. It can be seen that the average T_a in these apartments varied from 15.9℃ to 24.1℃, highlighting the fact that heating demand in each household was different.

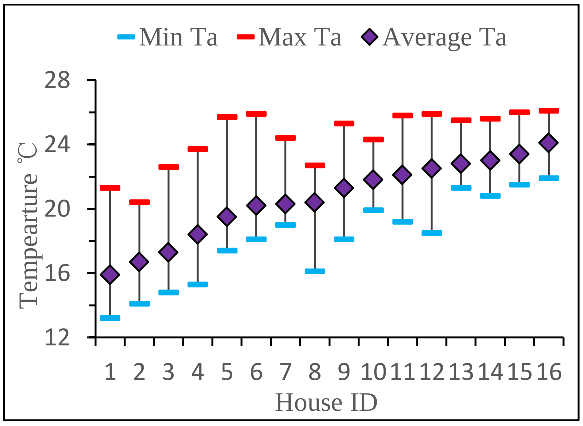

Figure 5 Temperature distribution in BJ-B apartments

Figure 6 show the relationships between heating energy consumption and mean heating temperature in BJ-B apartments. As all case apartments in BJ-B were located in the

[1] The initial costs of household gas boiler is 1467 US$. Assume it can work 15 years, so the average cost is 97.8 US$/a.

[2] The initial costs of central heating facilities was excluded. Because most of them are public infrastructure. If this part of investigation were taken into consideration, the heating fee of BJ-A would be higher.

same community, and had similar building construction, factors like building envelops and heating system efficiencies were rather secondary to influence heating energy consumption. Therefore, it can be concluded that the mean heating temperature is the major factor that influences heating energy consumption.

Besides mean heating temperature, some residents thought proper T_a control might conserve heating energy. Figure 7 illustrates three T_a control modes: mode1 had a similar mean internal temperature as mode2, but T_a fluctuated more. Mode3 had similar T_a fluctuation as mode2, but the mean heating temperature was lower. We found that the gas consumption of space heaters in mode2 and mode3 were obviously different, while the gas consumption of mode1 and mode2 were quite similar. Therefore, in terms of T_a fluctuation, mean heating temperature was the main factor influencing heating gas consumption in BJ-B apartments. However, it is worth noting that if T_a can fluctuate properly according to occupants' lifestyles, it can improve the occupied indoor thermal environment.

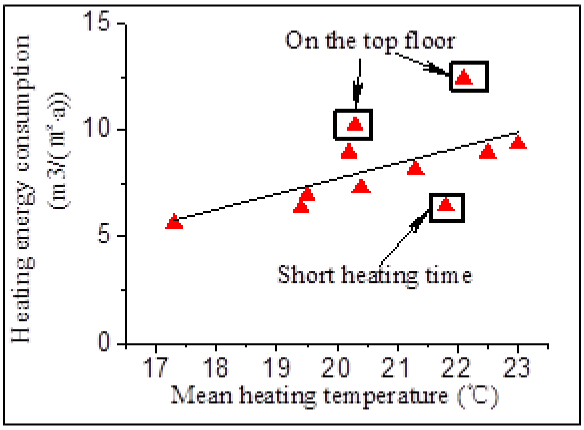

Figure 6 Relationships between heating energy consumption and the mean heating temperature

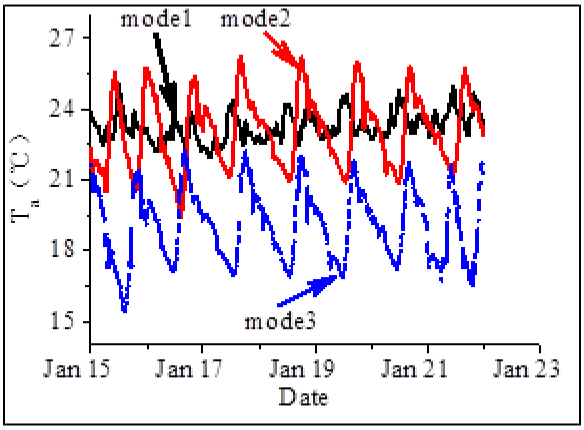

Figure 7 Three T_a control modes

4.3 What happened behind individual control approaches?

The above discussions demonstrated the diversity of occupants' choices when they were confronted with the trade-off between thermal comfort and heating fee. Exactly due to this kind of trade-off, Residents were encouraged to choose different indoor thermal conditions and corresponding adaptive behaviors. So, what happened during the process of the trade-off? What kind of role does individual control play?

To illustrate how occupants adjust to the environment with and without personal control over indoor thermal conditions, Figure 8 shows the adaptive behaviors among groups BJ-A and BJ-B. There are many forms of adaption in residential buildings, such as adjusting clothing, opening windows, drinking cold or warm drinks, etc. However, occupants in BJ-B apartments have more effective approaches for dealing with non-neutral thermal conditions because they can create preferable indoor thermal conditions by resetting the space heating temperature lower or higher as necessary. This may be a plausible explanation for why BJ-B apartments have a higher percentage of occupants who want to maintain their indoor thermal conditions. Upon closer examination of the frequency of each adjustment approach in BJ-B buildings, it is interesting that occupants tended to choose a lower heating temperature first when they felt hot but chose to add clothing first whey they felt cold. We attribute this phenomenon to economic effects, as a lower space heating temperature will result in lower heating fees.

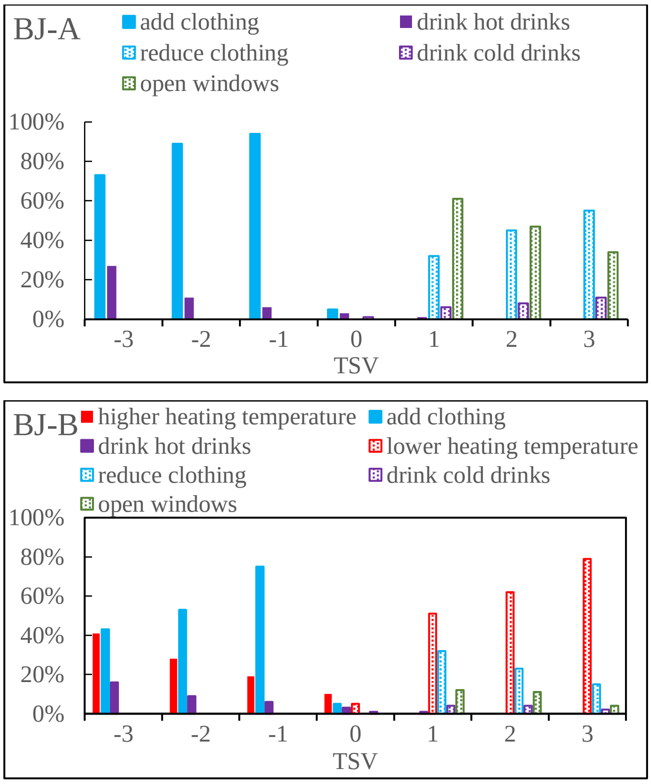

Figure 8 Adjustment approaches

Based on the analysis above, Figure 9 and Figure 10 illustrate occupants' trade-off processes in apartments with and without personal control over space heating systems. Why residents in BJ-B apartments reported more positive comfort related evaluation on their current internal thermal conditions? One reason may be that people with more personal control approaches tended to have increased ability to keep themselves in a comfortable state by removing the source of discomfort in a timely manner. Another reason may be that the feasibility of individual control over space heating systems allows residents to make their own trade-off between indoor thermal conditions and heating fees. The internal temperatures may depart from neutral comfort state (for instance, T_a was lower than the comfort temperature), but occupants were more likely to accept or adjust it instead of complaining immediately because it was their own choices.

However, for apartments without individual control, the situation was quite different. Firstly, occupants in such apartments had to accept their current internal thermal conditions passively, no matter it was comfortable or uncomfortable. When uncomfortable conditions occurred, less adaptive approaches were useful for them to adapt themselves to the indoor thermal environment. Secondly, there was no chance for them to make a trade-off between thermal comfort and heating fee. Once discomfort occurred, they were more likely to complaint the heating systems.

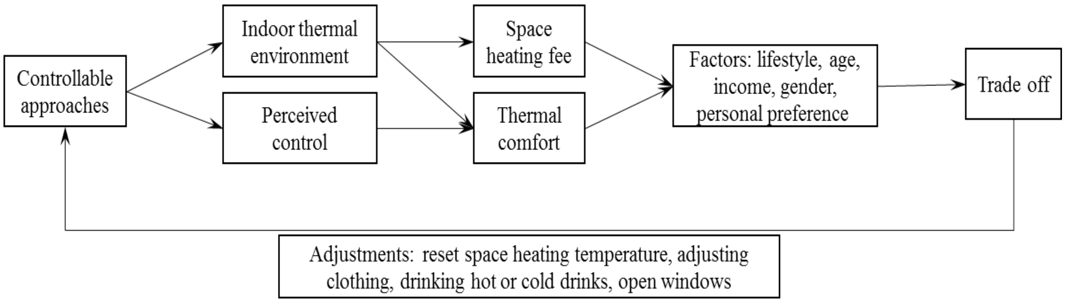

Figure 9 Trade-off processes in apartments with individual control

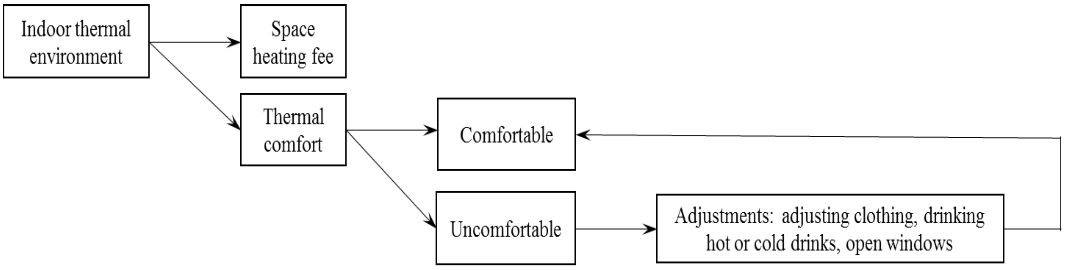

Figure 10 Passive acceptance processes in apartments without individual control

5 Conclusions

1) Occupants with capability of individual control had lower neutral temperature in winter time and reported more positive comfort-related perceptions than those without capability of personal control. The calculated neutral temperature of group BJ-B was 2.6 ^{o}C lower than group BJ-A, which indicates that occupants in BJ-B were more likely to vote neutral thermal sensations. To validate whether the difference in thermal comfort is mainly due to different degrees of personal control, we tried to compare the indoor thermal conditions of BJ-A and BJ-B apartments by conducting an independent samples t-test (as shown in Table 5) and by mapping the distribution of indoor thermal conditions corresponding to the questionnaires (as shown in Figure 2). In these analyses, we observed no significant differences between groups BJ-A and BJ-B, except that BJ-A apartments might have had an indoor temperature higher than 26^{o}C. But the difference was quite small and was precisely due to a lack of personal control. Additionally, although the difference in neutral operative temperature between BJ-A and BJ-B apartments was 2.6^{o}C, the differences in air temperature, humidity, and wind velocity were rather small. Furthermore, we tried the best to collect more evidences to support the effects of individual control from previous studies. Therefore, we believe the difference in thermal comfort is mainly (if not purely) due to the difference in personal control.

2) The capability of individual control over space heating systems allow residents to make their own trade-off between perceived thermal comfort and the space heating fees. Indeed, residents with higher degrees of personal control capability tended to have increased ability to keep themselves in a comfortable state by removing the source of discomfort in a timely manner. Except of this perceived control effects, we believe the feasibility of individual control and the more flexible payment mode in individual space heating apartments can also encourage residents to make their own choices between thermal comfort and heating fee. This may be why BJ-B occupants tended to choose a lower heating temperature first when they felt hot but chose to add clothing first whey they felt cold (as shown in Figure 8). And this can also explain why no overheat situations occurred in BJ-B apartments (as shown in Figure 2). These findings can serve as good reference when we choose the way to pay for our comfort.

3) It is recommended that occupants be offered sufficient opportunities to interact with the thermal environment through individual adaptive approaches such as operable windows, personal fans or terminal controllable HVAC systems. It appears that the best way to meet occupants' thermal comfort demand is to allow them make their own choices based on individual desires. This is especially true in residential buildings, where differences in personal preferences and lifestyle may be more pronounced, and individual adaptive approaches is a feasible way to offset these inherently different space conditioning demands.

6 Acknoledgements

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