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Indoor climate experience, migration, and thermal comfort expectation in buildings

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ABSTRACT

Advances in heating, ventilation and air conditioning (HVAC) technologies have dramatically improved the indoor thermal environment, but attention should be paid on how this would affect building occupants' thermal comfort perception. In this paper, we studied the mutually dependent relationship between indoor climate experience and occupants' comfort expectation. An intriguing experiment was conducted in China where wintertime indoor thermal environments in northern cities (with district heating) are much warmer than in southern region (without district heating). By analyzing the 4411 responses from four college-aged subject groups with different indoor thermal history, two interesting findings emerged. Firstly, people's understandings of thermal comfort change with their indoor thermal experiences. Those permanently live in lower-grade non-neutral thermal environment can achieve similar thermal comfort perception as those who live in long-term comfortable thermal conditions. Secondly, the dynamics of building occupants' thermal comfort adaptation project asymmetric trajectories. It is much quicker for occupants to accept neutral indoor climate than to lower their expectation and adapt to under-conditioned environments. These two phenomena can be well described by the index "demand factor", which can serve as a reference for future thermal comfort study.

KEYWORDS

Adaptive thermal comfort; thermal comfort expectation; thermal experience; indoor thermal environment; migration

1 INTRODUCTION

1.1 Air-conditioning and indoor thermal environment

Climate change is one of the major urgent issues we humans have to face in this century. But when talking about climate change most people will think of outdoor global warming while few can notice the changes in indoor climates we experience. In fact, our living places have always been 'evolving', from caves and wild fields in primitive age to ancient buildings with exquisite shapes and styles, and to modern buildings with advanced Heating, Ventilation and Air-Conditioning systems (HVAC). Especially since the appearance of air-conditioning in the last century, the thermal environment in modern buildings has been tightly controlled with a goal of creating thermal neutrality, emphasizing conditions that are constant through time, and uniform through space. Unfortunately, this trend is also associated with increased energy use to maintain these conditions. One way to mitigate climate change through reduced energy use in buildings is to re-evaluate what actually makes us comfortable.

The rapid advances in air conditioning technologies plus the increasing affordability have induced sharp increases in the air conditioner (AC) penetration. Figure 1 shows trends in different countries' AC penetration or adoption rates in the residential building sector. Although the growing period in different countries varied, the sharp increasing trends in these economic or demographic superpowers were shocking. A study [1] looked in particular at Mexico, where AC penetration was only about 13% in 2012 and forecasted that as people get richer, those living in warm climates will flock to AC with 2.7% ownership growth per $1,000 of annual household income. More worrying, similar things will happen not only in Mexico but also in low and middle-income countries around the world, especially in warm and tropical countries with large populations like India, Brazil etc.

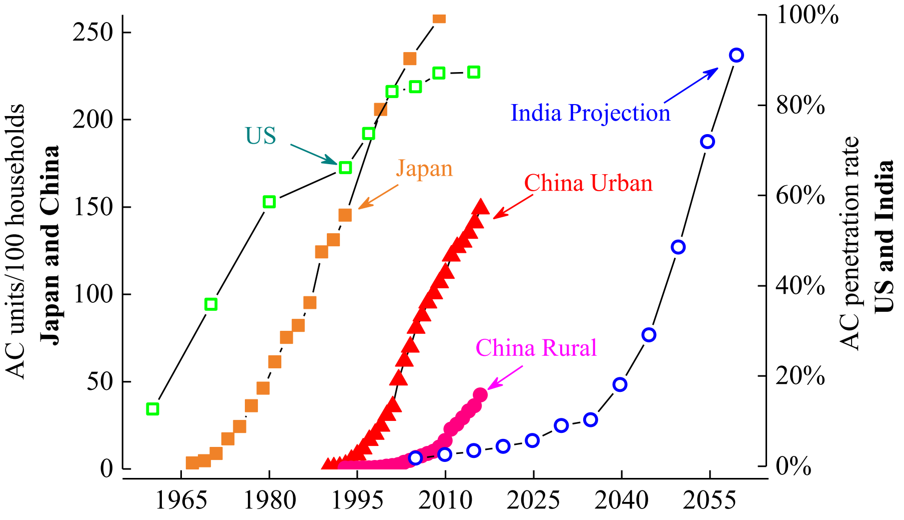

Figure 1 Increasing trend of Air Conditioner penetration or adoption rate (US data is from reference [2], Japanese data is from [3], Chinese data is from [4], India data is from [5])

The mutually dependent relationship between users' comfort expectation and HVAC technological development in western countries was noticed by Reyner Banham in the 1960s [6]. He stated that the most significant architecture changes caused by artificial environmental control development involve the manifestation of expectation changes, including both changes in user's needs and changes in methods of servicing users' needs. In the 1990s, Kempton [7] mentioned that the relationship between comfort expectations and air-conditioning, at least in the US, became so strong that it was often referred as an "addiction" similar to clinicians with respect to drugs. At present, the escalating AC market penetration in developing countries indicate that this kind of "addiction" not only happened in the US but also is happening in global demographic superpowers like Mexico, Brazil, India, and China.

The excessive need for comfort brought about indoor thermal environment homogenization, compressing the wide "natural range" of indoor temperature to narrow thermal neutralities [8]. The pervasiveness of HVAC throughout homes, workplaces, and transport makes our daily thermal exposures ever closer to theoretically ideal conditions: warm indoor environments being cooled while cool conditions being heated. The benefits of being able to mechanically heat and cool our buildings to eliminate uncomfortable conditions are widely accepted, of course. The question becomes – what is "ideal", and how narrowly or universally are ideal conditions defined? Taking wintertime indoor residential temperature as an example, Figure 2 shows its temporal shifting trends in countries like US, UK, northern Japan and China. It shows that typical indoor winter temperatures in these countries are narrowing over time, converging to some neutral temperature of about 20°C. Some researcher even named this trend as ‘homogenization of built environment’ [9] and ‘comfort capsules’ [10].

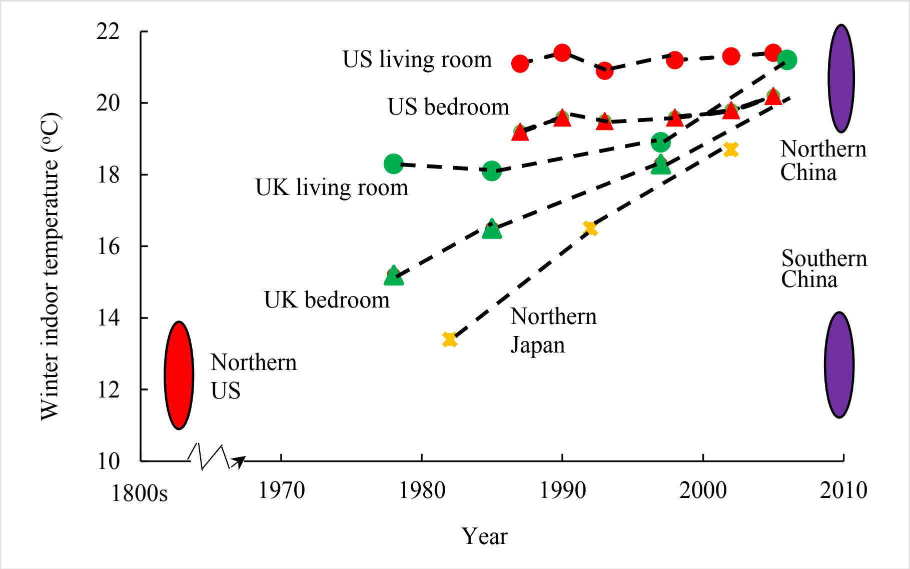

Figure 2 Historical trends of wintertime residential temperatures (US 1988-2008 and UK Sources are based on the review work of [11]; US 1800s [12]; Northern Japan [13]; China [14,15])

1.2 Thermal comfort expectation

Under the contexts of “indoor climate homogenization”, researchers are questioning whether such improvement in the indoor thermal environment has produced a proportionate increment in building occupants’ thermal satisfaction. Analyzing the ASHRAE database field study data, Arens et al. [16] showed that tight “class A” temperature control does not necessarily translate into higher thermal comfort evaluation compared with less tight “Class C” control. About 20% of building occupants reported their thermal environment uncomfortable no matter how tightly their thermal environment was controlled. Usually, such thermal discomfort complaints were explained by the interpersonal difference in thermal comfort demand and local thermal discomfort. But it leads one to question what is really meant by “classes” of environments. While early definitions tied the classes to the tightness or narrowness of the temperature set-points, perhaps it should be more related to the degree of personal control occupants have. However, the findings suggest another question we might ask. Will people living in what might be considered a “high quality” indoor environment (which, admittedly, can be defined in various ways) have their expectations raised, thereby leading to higher demands or higher frequency of complaints, while their counterparts with lower quality (or perhaps simply “more variable”) indoor environments unconsciously lower their thermal demand by adaptation? This question goes very core to the notion of thermal comfort expectation, which was firstly acknowledged in McIntyre’s work [17]. In the 1990s, Brager and de Dear [18,19] introduced the expectation concept into thermal comfort research field as a psychological adapting approach explaining why people are more accepting of the wider ranges of thermal conditions in naturally ventilated building environments. In 2002, Fanger and Toftum [20] induced the “expectation” as the seventh parameter in their Predicted Mean Vote (PMV) equation to extend PMV application in non-air-conditioned buildings in warm climates.

Although few studies have investigated the issue of expectation directly, some studies begin to allude to the potential effects. For example, a study by Nicol and Humphreys [21] found the comfortable indoor temperatures in heated or cooled office buildings in the 1990s were much more tightly clustered than those observed in 1970s.

Rajasekar [22] in their field study found that people in the hot humid climatic region of India had a thermal expectancy factor of 0.7. Andamon et al [23] studied how the modern transformations, first colonization, and then the introduction of air conditioning changed the Philippine people's understanding of normal and ordinary conditions of comfort. One of their conclusions is that the social understanding of comfort and its transition is malleable. Amin et al [24] investigated the influence of occupants' thermal history on the use of controls and indoor temperature preference in a newly built student hall in the UK. Their result indicates the average indoor temperature of residents from warm climates was 2.3 °C higher than those from cool climates. Wang et al [25] showed that people in the severe cold area of China tended to get used to the indoor temperature gradually if their apartments were overheated.

While these studies hint at the notion of thermal comfort expectations, they fail to offer solid evidence supporting the impacts of expectation, which is a complex combination with many confounding factors such as cultural difference and economic level. Direct empirical data needed to elaborate the underlying principles and dynamics of comfort expectation are yet to be produced. Given that the global demographic superpowers like India and China are embarking upon tremendous construction boom, the significance of thermal comfort expectation and their potential impacts on building design and operation cannot be overstated.

1.3 The objective of this study

In a previous paper [26], we revisited the notion of comfort expectation and designed an intriguing field-based experiment in China to explore the inherent principle of thermal comfort expectation. The current study further analyzed the experimental results in a more thorough way to answer the following questions: (1) what is the relationship between people's indoor thermal experiences and their thermal comfort expectations? (2) how can one describe the changes in thermal comfort expectation? (3) what are the dynamic characteristics of thermal comfort expectation?

2 METHODS

2.1 Wintertime indoor temperatures in China

Since the 1950's, China has been implementing a space heating policy setting the Huai River as the boundary of centralized district heating between southern and northern cities. According to this policy, centralized district heating networks were only established in northern cities, covering most of the Severe Cold and the Cold zones. Meanwhile, district heating systems were prohibited in southern China which includes the Hot Summer & Cold Winter zone, the Temperate zone, and the Hot Summer & Warm Winter zone.

As a legacy of the Huai River policy, recorded wintertime indoor temperatures in northern cities have been much warmer than those in southern cities. This generalization is supported by many field studies with thermal environment measurements, as partially summarized in Table 1. One typical example is the large-scale survey done by Yoshino et al [14], focusing on residential indoor thermal environments in major Chinese cities in different climate conditions. In this study, surveys were simultaneously conducted in what will be characterized as northern China (Harbin, Urumqi, Beijing, Xi'an), and in southern China (Shanghai, Chongqing, Changsha, Kunming, Hong Kong), and others. The measured results collectively support the finding that, in cold northern cities with centralized heating networks, wintertime indoor temperatures were relatively stable around 20^{o}C. At the same time, indoor temperatures in southern cities which lacked district heating systems, especially those in the Hot Summer & Cold Winter zone, were typically as cold as 8 to14°C. A similar generalization can be observed in the humidity measurements as well, where the relative humidity in northern cities was about 30%, while that in southern cities could be as humid as 70%.

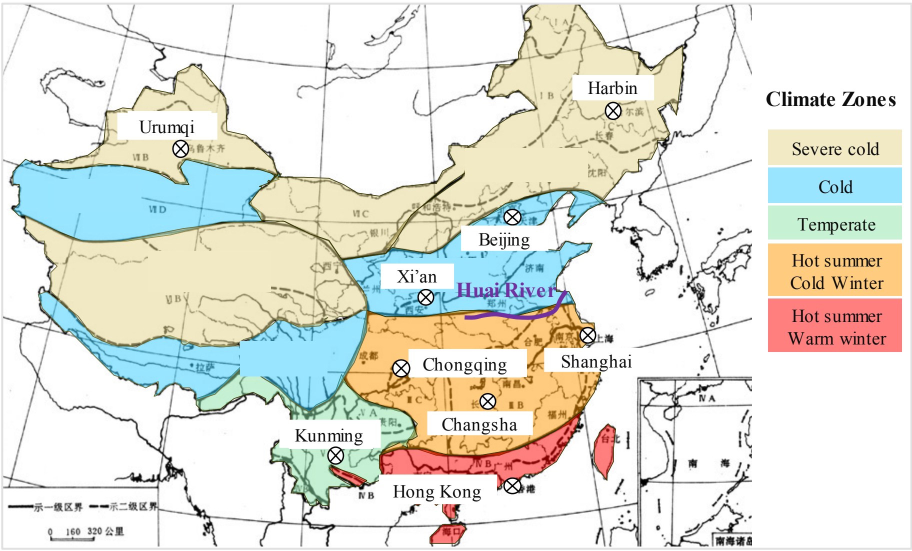

Figure 3 Heating zones in China

Table 1 Measured residential wintertime indoor temperature and humidity in typical cities

Climate zones	Space heating days	Cities	Indoor temperature (^oC)	Indoor relative humidity (%)	Reference
Northern China					
Severe cold	150-200	Harbin	20-24	20~35	[14, 27]
		Urumqi	20-24	20~35	[14]
Cold	90-150	Beijing	19-24	25~40	[14,28]
		Xi’an	19-24	20~40	[14]
Southern China					
Hot summer Cold winter	---	Shanghai	8-14	65~80	[14,28]
		Chongqing	8-14	70~85	[14, 29,]
		Changsha	8-13	70~85	[14, 30]
Temperate	---	Kunming	13-17	55~75	[14]
Hot summer warm winter	---	Hong Kong	16-23	60~80	[14]

2.2 Subject groups

The indoor temperature difference between northern and southern China created natural conditions for an intriguing experiment. In addition to looking at differences simply between people who lived in these different regions, we also wanted to look at the differences in people who grew up in that region versus those who moved between regions. With this in mind, the research team defined four subject groups: 1) subjects who had always lived in northern China (N-N); 2) subjects who had moved from southern China to northern China (S-N); 3) subjects who had always lived in southern China (S-S); and 4) subjects who had moved from northern China to southern China (N-S). As subjects’ indoor thermal experience is closely related to their geographical location, it is important to identify where they live now and where they came from. In this study, northern subjects mainly came from or lived in cities like Beijing, Tianjin, Xi’an and Harbin, southern subjects mainly came from or lived in cities around Yangzi River Basin such as Shanghai, Chongqing, Wuhan, and Changsha.

Although there were clear differences in the availability of centralized district heating in the two regions, we also wanted to examine the influence of localized space heating on indoor temperature. Figure 4 shows significantly different patterns in what kinds of local heating terminals were utilized by respondents in the two regions. In the colder northern China regions, 81% of respondents used radiator heating or floor heating, compared to southern China where 91% percent of respondents used air source heat pumps, electronic heater or just no heating. To ensure a cleaner separation between the regional differences in both wintertime indoor temperatures, and the types of heating systems that were used, the following analysis excluded subjects who lived in southern China but utilized the systems more common to northern China - floor heating and radiator heating, and also excluded those living in northern China but without the availability of district heating facilities. In total, 4411 respondents among the original 5168 were selected for analysis. As shown in Table 2, similar numbers of male and female subjects were recruited, and over 80% of each subject group were young college students aged 20-30 years old, aiming to minimize the confounding effects of age.

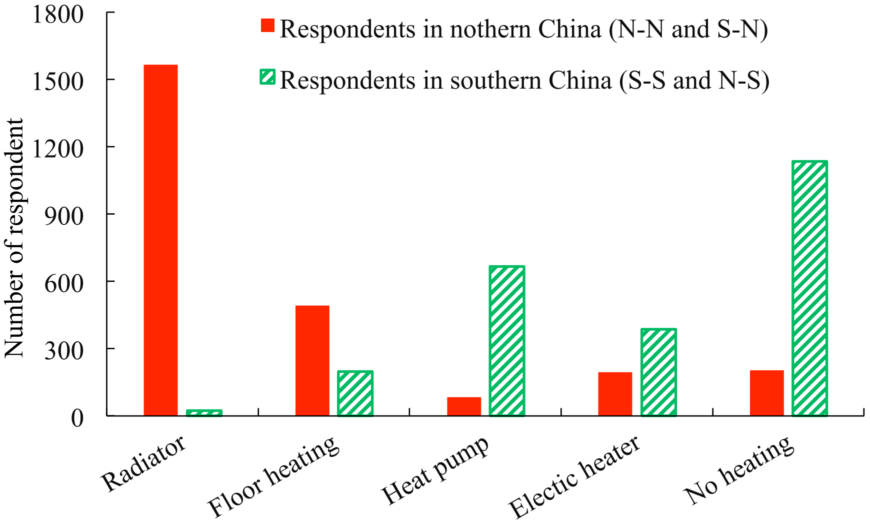

Figure 4 Statistics of heating facilities

Table 2 Subject group information

Group	Winter indoor thermal experience	Number of subjects			Age				
		Total	Male	Female	<20	20~30	30~40	40~50	>50
N-N	always lived in northern China	988	430	558	73	498	128	177	112
S-N	moved from southern to northern China	1138	628	510	169	912	14	22	21
S-S	always lived in southern China	1616	644	972	124	1301	65	54	72
N-S	moved from northern to southern China	669	393	276	21	562	40	26	20

2.3 Survey

The online survey was administered during two periods: December 2014 through February 2015, and December 2015 through February 2016. These two periods were typically the coldest time during a whole year in China. In this way, the difference in indoor temperature between southern and northern regions can be guaranteed because southern China homes lacked continuous space heating while northern area homes had centralized space heating. Subjects were asked to evaluate the general wintertime indoor thermal environment of their hometown based on their memory and also what they think about indoor climates in general of their current home. The word "general" refers to the overall impression during the wintertime instead of "right here right now" surveys that are often used in thermal comfort field studies. For example, subjects in the N-S group were asked to assess both North and South areas; for the North, it's their memory before they migrated, and for the South, it's their general impression on current home. The survey was focused on residential buildings such as a house, apartment or dormitory. The survey questions all used seven-point scales and asked about thermal sensation vote, thermal comfort vote, humidity sensation, humidity comfort, and overall acceptance. The words used in each of these seven-point scales are depicted in

Table 3.

Table 3 Question scales

	Thermal sensation	Thermal comfort	Humidity sensation	Humidity comfort	Overall acceptance
3	Hot	Very comfortable	Very dry	Very comfortable	Very acceptable
2	Warm	Comfortable	Dry	Comfortable	Acceptable
1	Slightly warm	Just comfortable	Slightly dry	Just comfortable	Just acceptable
0	Neutral	Unclear	Neutral	Unclear	Neutral
-1	Slightly cool	Just uncomfortable	Slightly humid	Just uncomfortable	Just unacceptable
-2	Cool	Uncomfortable	Humid	Uncomfortable	Unacceptable
-3	Cold	Very uncomfortable	Very humid	Very uncomfortable	Very unacceptable

2.4 Data analysis

Calculations were made for the descriptive statistics (mean, standard deviation) and the differences between means of thermal sensation vote and thermal comfort vote. Two sample T-tests with equal variances were applied to verify the significance of the differences among groups. For all tests, the results were considered statistically significant when $p \leq 0.05$. The interpretation of the outcome was as follows: $p \leq 0.001$ means highly significant, $0.001 < p \leq 0.01$ means significant, $0.01 < p \leq 0.05$ means weakly significant, and $p > 0.05$ means not significant. Due to the size of the samples possibly confounding the T-test result, for each comparison, we calculated the effect size (Cohen's d) to quantify the impact of sample sizes on the statistically significant differences. The interpretation of the outcome followed the thresholds provided by Sawilowsky [31]: d=0.01 means very small difference, d=0.2 means small difference, d=0.5 means medium difference, d=0.8 means large difference, d=1.2 means very large difference, and d=2.0 means a huge difference. All statistical analysis was performed using Excel version 2016.

3 RESULTS

3.1 Indoor thermal history and thermal adaptation

Table 4 summarizes each group's evaluations of the general indoor thermal environments of residential buildings in southern and northern China. Two initial major findings can be drawn from it. Firstly, the N-N group's thermal sensation vote (TSV) was dominated by 'neutral' and 'warm', while the majority of S-S group felt 'cool' and 'slightly cold'. This is consistent with the earlier mentioned thermal environment generalization between northern and southern China. But what's interesting is that although these two groups had different thermal sensations, they didn't show a significant difference in their thermal comfort vote (TCV). Feedback from both groups showed that a significant majority of TCV fell in the "comfortable" range. Secondly, the two migrating groups (N-S and S-N) had similar TSV and TCV evaluations with N-N group on northern China's wintertime indoor temperature, but significantly worse TSV and TCV (felt colder and more uncomfortable) than S-S group on southern China's indoor temperature.

Table 4 Different subject groups' indoor thermal environment evaluation. (Note, T-test with no significant difference was labeled as 'o'. Effect size with Cohen's d larger than 0.7 was marked as bold font. As each group were asked to give evaluations to their hometown and their current abode place, N-S, and S-N groups had evaluations on both North and South, and N-N and S-S groups had two times of voting number than their example number)

Subject groups		N-N	S-S	N-S		S-N	
Region		North	South	North	South	North	South
Thermal sensation vote (TSV)	Cold	14	380	3	154	1	266
	Cool	57	748	25	243	17	543
	Slightly cool	343	1252	42	107	54	257
	Neutral	1124	745	415	118	677	58
	Slightly warm	249	96	155	35	200	13
	Warm	151	9	25	11	151	1
	Hot	38	8	4	0	38	0
Mean		0.08	-1.17	0.17	-1.49	0.46	-1.87
SD		0.98	1.03	0.81	1.26	0.95	0.87
T-test with equal variances	Compare with N-N group	---	<0.001	o	<0.001	o	<0.001
	Compare with S-S group	<0.001	---	<0.001	<0.001	<0.001	<0.001
Effect size (d)	N-N as control group	---	**1.28**	0.09	**1.62**	0.39	**2.00**
	S-S as control group	**1.22**	---	**1.31**	0.32	**1.59**	0.68
Thermal Comfort vote (TCV)	Very uncomfortable	24	73	3	43	7	44
	Uncomfortable	139	334	16	118	42	248
	Just uncomfortable	309	693	44	119	141	342
	Unclear	204	374	46	56	112	114
	Just comfortable	798	1385	304	182	489	298
	Comfortable	304	286	193	38	321	83
	Very comfortable	198	87	63	13	26	9
Mean		0.68	0.20	1.19	-0.32	0.85	-0.42
SD		1.42	1.35	1.12	1.59	1.17	1.40
T-test with equal variances	Compare with N-N group	---	0.041	o	<0.001	o	<0.001
	Compare with S-S group	0.041	---	o	<0.001	<0.001	<0.001
Effect size (d)	N-N as control group	---	0.34	0.36	**0.70**	0.12	**0.78**
	S-S as control group	0.36	---	**0.73**	0.38	0.48	0.46

Figure 5.a shows the overall distribution of thermal sensation votes between different thermal history groups, with the upper bars representing people who had moved between regions, and the lower bars representing people who remained in the same region. There were stark differences in people's thermal sensation votes when asked about the two regions. The majority of occupants' impression of the northern areas were either neutral or warm (and of those who

expressed cold sensations, there were more from people who always lived in that region, compared to those who moved either from or to the region). In comparison, over 70% of thermal sensations about southern China were dominated by cold side votes, with the strongest impressions (over 90% cold) from people who no longer lived there are were voting about their memory of the experiences.

Similarly, Figure 5.b compares the overall distribution of comfort perceptions between different groups. Despite the widely discrepant indoor temperatures and thermal sensations (Figure 5.a), the N-N and S-S groups had close thermal comfort evaluations; both groups had a majority of positive evaluations, accounting for 71% and 60% respectively. But the two migrating groups (N-S and S-N) expressed completely different comfort perceptions about northern and southern China, regardless of in which direction they migrated. They both gave overwhelmingly positive feedbacks on northern China's wintertime indoor thermal environment (65% to 83% comfortable) while giving more negative evaluations of the southern area (only 41% to 52% comfortable).

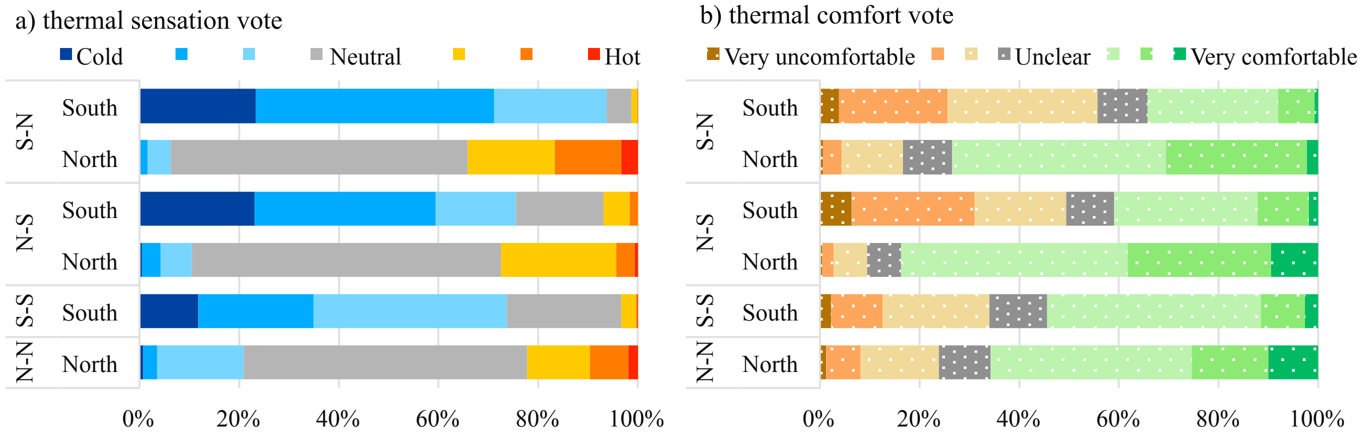

Figure 5 Different groups' thermal perception.

To better understand the complicated relationships between each groups' indoor thermal history and their corresponding thermal comfort perception, an index named 'comfort score' was defined as Equation 1. This score would return a value between +1.0 if all of the votes were in the comfortable range, and -1.0 if all the votes were uncomfortable. To do the calculation, the votes from 'just uncomfortable' to 'very uncomfortable' votes were categorized as the '***uncomfortable side***', while votes from 'just comfortable' to 'very comfortable' were grouped into the '***comfortable side***'. As for the 'unclear' votes, it was split into half and half - 50% were regarded as comfortable and the rest 50% were grouped into the uncomfortable side.

Figure 6 compares the different groups' comfort scores and shows that people living in colder indoor thermal environments (group S-S) had quite similar comfort scores with those living in neutral-to-warm indoor conditions (group N-N), despite the fact that they experienced physically different indoor thermal environment. But for people who migrated and therefore experienced both non-heated and heated indoor thermal environments (group N-S and S-N), they reported higher comfortable scores for the northern region. This suggests that people's understanding of thermal comfort is malleable, depending on their previous thermal experience. People in the N-N group had been shown to adapt to thermal neutrality if that was what they were exposed to repeatedly. Alternatively, people in the S-S group could also adapt to indoor climates that deviated from thermal neutrality. Another interesting phenomenon is that the N-

S group voted the highest comfort score for the northern region based on their memory while the S-N group had the lowest comfort score for their memory of the southern region. It indicates that both comfortable and uncomfortable memories can be enlarged when compared to the current comfortable or uncomfortable perceptions.

$$\text{Comfort score} = \frac{\text{comfort votes} - \text{uncomfortable votes}}{\text{Total votes}} \qquad \text{Equation 1}$$

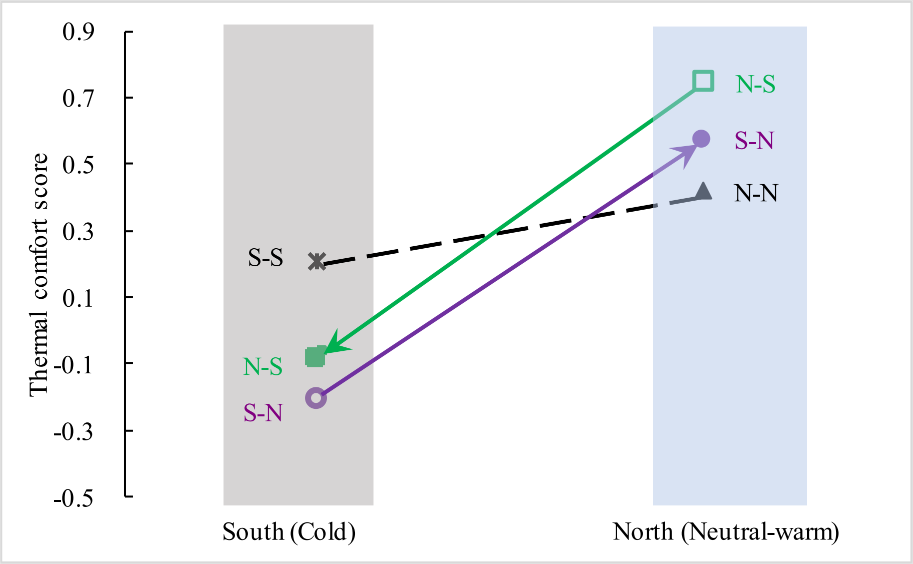

Figure 6 Thermal comfort scores (note that the “cold” and “neutral-warm” labels refer to the *indoor* environments that are characteristic of these regions, not the outdoor climate)

3.2 Dynamic changes of thermal adaptation

The above result shows a mutually dependent relationship between indoor thermal environment and occupants’ understanding of thermal comfort, which is reflective of thermal adaptation. But how do repeated exposures to different indoor temperatures shape our expectations of the thermal environment? To study this, we further sub-divided the migrating groups (S-N and N-S) on the basis of duration in the new region following migration. The number of samples for each subgroup is shown in Table 5.

Figures 7a and 7b show the trend of comfort evaluations of the N-S and S-N subgroups, respectively, based on how long they had lived in the new region. In Figure 7a, it can be seen that comfort evaluations of the migrating northerners started out at the lowest (30.4%), and then improved gradually as people lived in the south longer. People who had lived there for at least four years had essentially the same responses (58.9% comfortable) as those who had always lived in the south (S-S group), as shown in the rightmost column. This can be regarded as an indicator that the migrated northerners required time to adapt to the non-heated southern environments, adapting more in each year after they migrated. This same pattern did not hold true, however, for people who migrated from the south to the colder north, as shown in Figure 7b were there is a very small variance in the S-N subgroup’s comfort evaluations. The proportion of comfortable votes stayed within 72.5%~82.6% with no discernable pattern based on how long ago they had migrated. These levels were all just slightly higher than those who had always lived in the north (N-N group, at 71%), but not as high as those who always lived in the south, where they had come from (S-S group, at 60.2%). This suggests that people who migrated from the south to the neutral-warm heated indoors in northern cities adapted very quickly, even less than 1 year [32].

Table 5 Subgroup samples based on time in new location following migration

	Less than 1year	1~2 year	2~3 year	3~4 year	More than 4 years	Total
N-S	106	93	111	144	216	669
S-N	228	132	152	324	302	1138

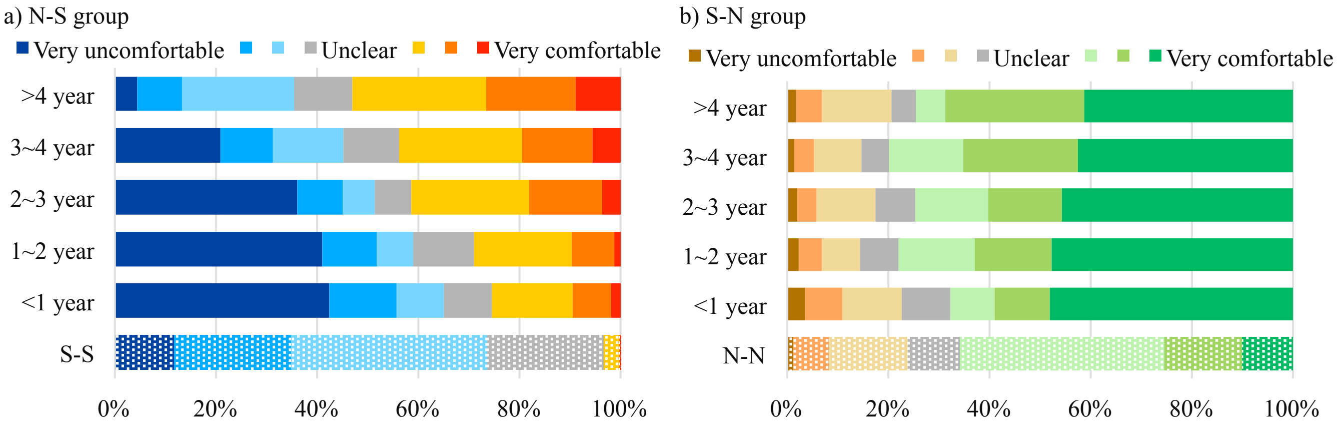

Figure 7 The changes of migrating groups' comfort evaluation

Figure 8 compares the dynamic changes of different groups' comfort score, as expressed in Equation 1. Consistent with what we saw in Figure 7, the comfort score of N-S subgroups climbed over time until it drew close toward that of S-S group. Meanwhile, the comfort score of S-N was maintained at a high level with small variance in relation to the time following migration. These two different trends may reflective of the different adaption patterns of the N-S and S-N groups. The former group migrated from a comfortable heated environment to a less comfortable non-heated environment, thus their adaption was relatively slow or reluctant; the latter group migrated from a non-heated environment to colder outdoor climate but with a neutral-warm heated indoor environment, and it appears that the adaptation process was relatively quick.

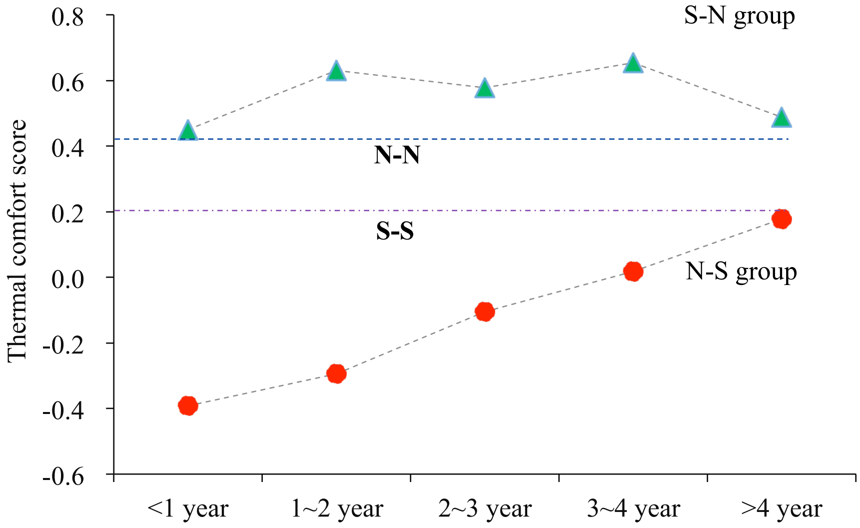

Figure 8 Different groups' comfort scores. (Note, positive values mean there were more comfortable as uncomfortable votes, and vice versa)

The above comfort score analysis helped to understand the dynamics of thermal adaptation in this region to some extent, but this method has limitations as well. For example, it didn't reveal any nuances in the adaptation process of the S-N group. In order to compare different groups' adaptation process in more detail, we proposed a new metric, which was called the 'demand factor' (DF) index, to describe people' thermal comfort demand for thermal environment. The basic logic of the DF index is as follows: if a group of people has relatively high requirements (or expectations) of the indoor thermal environment, and a lower tolerance of uncomfortable conditions (i.e., deviations from thermal neutrality), the combination of these factors would lead to a bigger value of DF. On the contrary, if a group of people has relatively low requirements of the thermal environment, and a higher tolerance of uncomfortable conditions, this would have a smaller value of DF. To quantify this, we define DF as shown in Equation 2:

$$\text{Demand factor}_{\text{i}} = \frac{\sum_{\text{cold}}^{\text{hot}} \text{percentage of uncomfortable}_{\text{i}}}{\sum_{\text{cold}}^{\text{hot}} \text{percentage of uncomfortable}_{\text{baseline}}} \qquad \text{Equation 2}$$

Where 'i' means group$_{\text{i}}$, '$\sum_{\text{cold}}^{\text{hot}} \text{percentage of uncomfortable}_{\text{i}}$' means the sum of group$_{\text{i}}$'s uncomfortable percentages across the range of cold-to-hot thermal sensation votes, '$\sum_{\text{cold}}^{\text{hot}} \text{percentage of uncomfortable}_{\text{baseline}}$' means the sum of group$_{\text{baseline}}$'s uncomfortable percentages across the range of thermal sensation votes. It should be noted that the selection of the baseline, or reference, group is flexible. It can be a real group of people, or a hypothetical group determined using the PMV-PPD model. In this study, we selected the average of all the respondents as the baseline group, which includes S-S, N-N, S-N and N-S groups. When DF is >1, this means that group$_{\text{i}}$ had higher levels of discomfort, or a higher demand or expectations, compared to the baseline group, and vice versa when DF is <1.

Table 6 shows the relationship between uncomfortable votes (not including neutrality) and thermal sensation votes, and also the DF calculations, for the groups who have lived in each region all their lives. Within each thermal sensation category, the N-N group had higher uncomfortable votes than S-S group, which indicates that the N-N subjects had a higher demand for the thermal environment, and were less tolerant of conditions that deviated from thermal neutrality. This is also revealed as a higher demand factor for the N-N group. According to the definition of Equation 2 and the specific values listed in Table 6, the demand factor can be calculated as 0.8 for S-S group and 1.13 for N-N group.

Table 6 Uncomfortable rate and demand factor for N-N and S-S groups. (note that the percentage numbers in this table are uncomfortable percentage for each thermal sensation vote. That's why the summarization of the percentage row can exceed 100%.)

		Uncomfortable % for each thermal sensation vote							
		Cold	Slightly cold	Cool	Neutral	Warm	Slightly hot	Hot	**Demand factor**
Baseline group	Percentage	77%	54%	41%	14%	26%	60%	85%	**---**
	Number of vote	630	882	843	439	194	209	75	
N-N group	Percentage	95%	65%	44%	15%	28%	68%	90%	**1.13**
	Number of vote	13	37	151	169	70	103	34	
S-S group	Percentage	64%	52%	41%	14%	21%	35%	60%	**0.80**
	Number of vote	243	389	501	104	20	3	5	

The notion of demand factor can be extended to N-S and S-N subgroups. By comparing different groups' demand factor for the time since migration, Figure 9 shows the dynamic changes of each group's thermal adaptation. It's interesting to see that the two migrated groups, N-S and S-N, exhibited different patterns in their demand factor over time, which is reflective of the process of adaptation. The demand factor of the N-S group decreased gradually (implying a slow rate of adaptation). This suggests that even after more than 4 years, they still didn't fully accept the cold indoor thermal environment in southern China. In comparison, the demand factor of the S-N group increased rapidly in the first year and then maintained at a certain level, which means they adapted quickly to the northern China indoor environments, and within a year were responding similarly to people who had lived in northern China their whole lives.

Figure 9 also suggests that it may be quicker to develop higher expectations (i.e., have a higher demand factor) while it is slower to lower one's demand factor (i.e., become accustomed to less comfortable conditions), which indicates that thermal adaptation in buildings is asymmetric. For example, the N-S group is those people who migrated from a relatively comfortable neutral-warm indoor thermal environment to a more uncomfortable cold indoor environment. The gradual decrease of their demand factor was slow; it took them more than 4 years to lower their thermal demand to a level close to people who lived in southern China all their life. On the other hand, the S-N group are people who moved from a relatively cold indoor environment to a more neutral indoor environment. Their demand factor increased rapidly in less than 1 year, and then maintained at a high level similar to that of N-N group. In short, it is slow and perhaps a reluctant process for occupants to move a neutral to a cold indoor climate, while it is quick and perhaps more delightful to get accustomed to the thermally neutral lifestyle.

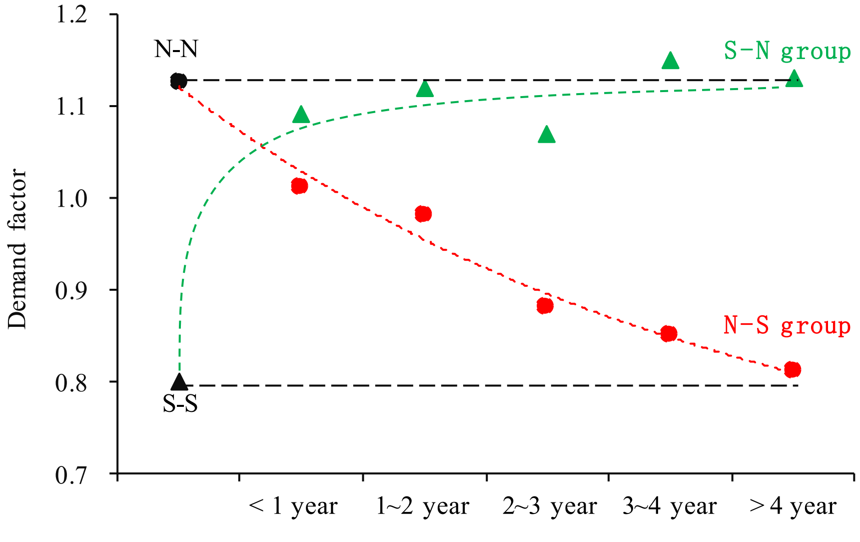

Figure 9 Dynamics of thermal demand factor

3.3 Dynamic changes of humidity adaptation

The above method can also be applied to analyze how people adapt to the different humidity environments. Table 7 presents each group's indoor humidity environment evaluation in southern and northern China. The N-N group's humidity sensation vote was dominated by 'neutral' and 'slightly dry', while the majority of the S-S group felt 'neutral' and 'slightly humid'. This is consistent with the earlier mentioned generalization about the humidity environment between these two regions. But what's interesting is that although these two groups had different thermal sensations, they didn't show a significant difference in their humidity comfort vote. Feedback from both groups showed a significant majority of "just comfortable" vote. For the two migrating groups (N-S and S-N), the N-S group thought that northern China (with 'neutral-dry' humidity environments) was more comfortable than southern China, while the S-N believed that the southern area (with 'neutral-humid' humidity environments) were more comfortable. In other words, they both perceived the humidity environments of their original locations to be more comfortable.

Table 7 Different subject groups' indoor humidity environment evaluation. (Note, T-test with no significant difference was labeled as 'o'. Effect size with Cohen's d larger than 0.7 was marked as bold font.)

Subject groups		N-N	S-S	N-S		S-N	
Region		North	South	North	South	North	South
Humidity sensation vote	Very dry	113	24	42	13	52	5
	Dry	259	145	89	21	181	21
	Slightly dry	738	211	131	36	699	89
	Neutral	770	1579	292	176	233	375
	Slightly humid	52	964	69	215	36	461
	Humid	22	236	36	185	23	139
	Very humid	13	73	11	43	14	48
Mean		0.74	-0.33	0.39	-0.87	0.88	-0.65
SD		1.00	1.00	1.27	1.21	0.98	1.02
T-test with equal variances	Compare with N-N group	---	<0.001	<0.001	<0.001	<0.001	<0.001
	Compare with S-S group	<0.001	---	<0.001	<0.001	<0.001	<0.001
Effect size (d)	N-N as control group	---	**0.96**	0.33	**1.24**	0.14	**1.15**
	S-S as control group	**0.96**	---	0.67	0.45	**1.08**	0.31
Humidity comfort vote (TCV)	Very uncomfortable	56	86	34	135	71	45
	Uncomfortable	141	163	52	113	136	152
	Just uncomfortable	203	251	159	92	364	204
	Unclear	250	194	114	104	122	106
	Just comfortable	918	1627	139	122	274	303
	Comfortable	283	673	99	77	126	196
	Very comfortable	126	238	82	26	56	132
Mean		0.61	0.88	0.32	-0.55	-0.13	0.39
SD		1.37	1.32	1.66	1.82	1.56	1.71
T-test with equal variances	Compare with N-N group	---	<0.001	<0.001	<0.001	<0.001	<0.001
	Compare with S-S group	<0.001	---	<0.001	<0.001	<0.001	<0.001
Effect size (d)	N-N as control group	---	0.20	0.20	**0.74**	0.50	0.14
	S-S as control group	0.20	---	0.40	**0.94**	**0.70**	0.34

Figure 10 compares different groups' "humidity comfort scores", i.e., looking at the difference between comfortable and uncomfortable votes, again using Equation 1 but using the humidity comfort votes shown in Table 7. As noted previously, the questions asked people to assess their perceptions of the indoor environment in each region – whether they lived there permanently, or migrated from or to the region. It shows that the S-S group permanently living in relatively humid climates had a quite similar indoor humidity comfort score (0.57) compared to the N-N group living in dry climates (0.47), despite the fact that they experienced quite different indoor humidity (shown in Table 1). However, people who migrated and therefore experienced both humid (southern) and dry (northern) indoor climates expressed much more positive evaluations of their original living places (humidity comfort index > 0) compared to relatively more negative evaluations of their current living places (humidity comfort index < 0). This means that when you look at impressions of a given region, groups who migrated to that region always had a lower humidity comfort index than those who either permanently or originally lived there. This phenomenon suggests that humidity comfort perception is long-lasting and is closely related to the environments you were exposed to growing up.

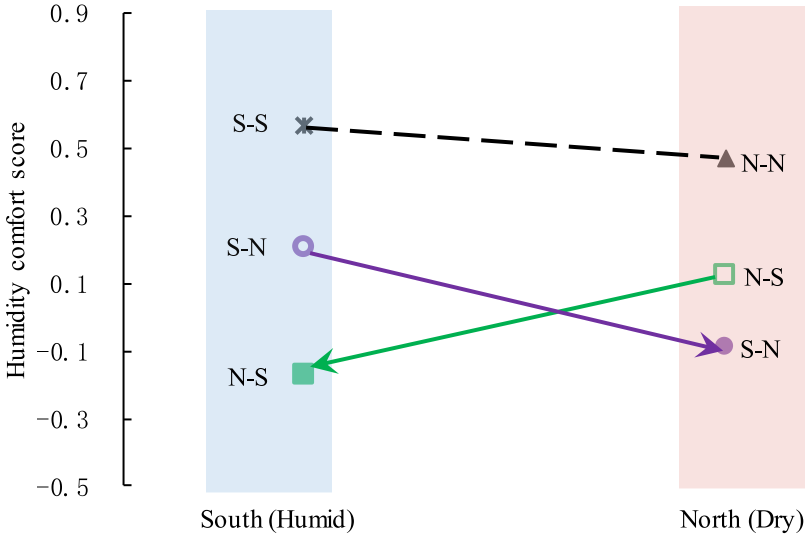

Figure 10 Humidity comfort evaluations of the south and north indoor environments

By comparing Figure 10 and Figure 6, one can notice that people adapt to temperature and humidity environments in different ways. For thermal comfort assessments shown in Figure 6, the indoor environments in the non-heated South China area are cold, and receive a lower comfort score, while the heated North China regions have neutral-warm indoor conditions, and received higher comfort scores. The S-N group migrated from a lower quality to the higher quality environment in terms of indoor temperature assessments, and the adaptation process was relatively quick; N-S group moved in the other direction, from a higher to lower quality indoor environment, and their adaptation is relatively slow. But for humidity environment shown in Figure 11, the situation is different. The southern area is humid while the northern side is dry, and both of them could be described as lower-quality in objective terms compared with an ideal 50% relative humidity. From this perspective, both S-N and N-S groups migrated from one poor-quality to another poor-quality humidity environment, and there was no adaptation – both groups gave a higher score to the region from where they originated.

Next, we want to examine the dynamic patterns of how humidity adaptation is influenced by the time since the migration of the N-S and S-N groups. Figure 11 shows different groups' demand factor from the view of humidity perception. As shown in the figure, the demand factors of N-N and S-S groups were slightly lower than that of N-S and

S-N. Immediately following migration, the DF of N-S and S-N both increased, showing their initial difficulty in adapting to the newer humidity, in either direction. As the time after migration increased, both N-S and S-N's demand factors decreased with time gradually, eventually getting close to, but still slightly higher, than people who have always lived in the same region. It appears that adaptation to new indoor humidity conditions is more difficult than for changes in indoor temperatures.

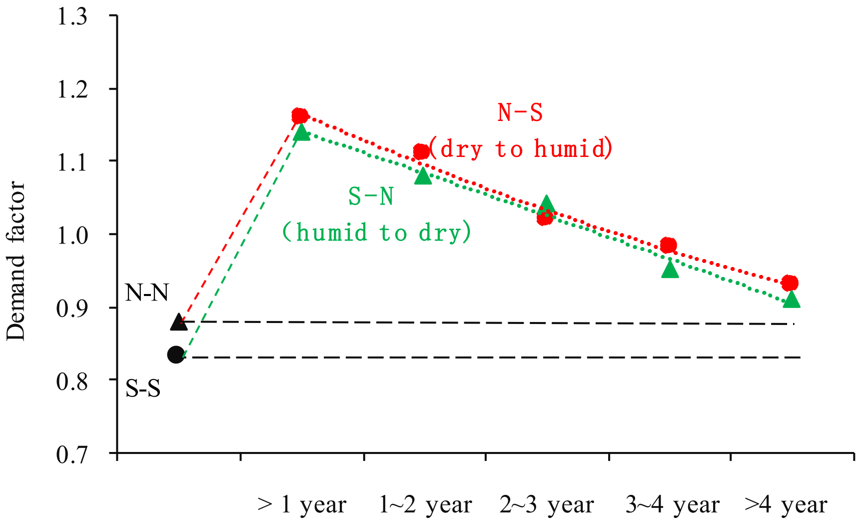

Figure 11 Dynamics of humidity demand factor

3.4 Overall acceptability

To better understand the extent to which temperature and humidity comfort influence people's overall acceptance, we used correlation analysis. First, to make the results more intelligible, the votes from 'just uncomfortable' to 'uncomfortable' votes were recoded as '***uncomfortable side***' with a value of ***'-1'***; votes from 'just comfortable' to 'comfortable' were grouped into '***comfortable side***' with a value of ***'+1'***; and the 'unclear' votes were assigned a neutral value of ***'0'***. At the same time, the overall acceptance votes were also simplified in a similar way. The votes from 'very acceptance' to 'just acceptance' were collapsed into a single category, '***acceptable side***' with a value of ***'+1'***; votes from 'very unacceptance' to 'just unacceptance' were recoded into '***unacceptable side***' with a value of ***'-1'***; and the 'neutral' votes were assigned a value of ***'0'***. Then, correlations between overall acceptance rate and temperature and humidity comfort were analyzed, using the correlation coefficient r value to reflect the degrees of correlation between variables. Table 8 list the typical r values and the corresponding degrees of correlation.

Table 8 Correlation coefficient and degree of linear correlation

|r| value	1	0.8~1	0.3~0.8	0~0.3	0
Degrees of correlation	Completely correlated	Highly correlated	Moderate correlated	Low correlated	Uncorrelated

The results are shown in Figure 12, which suggests that there is a high correlation between overall acceptance and thermal comfort, where the correlation coefficients are generally above 0.8. Meanwhile, humidity comfort and overall acceptance showed a low correlation, with r values less than 0.5. This means that temperature had a higher influence on overall acceptability in the cases of space heating issues in China.

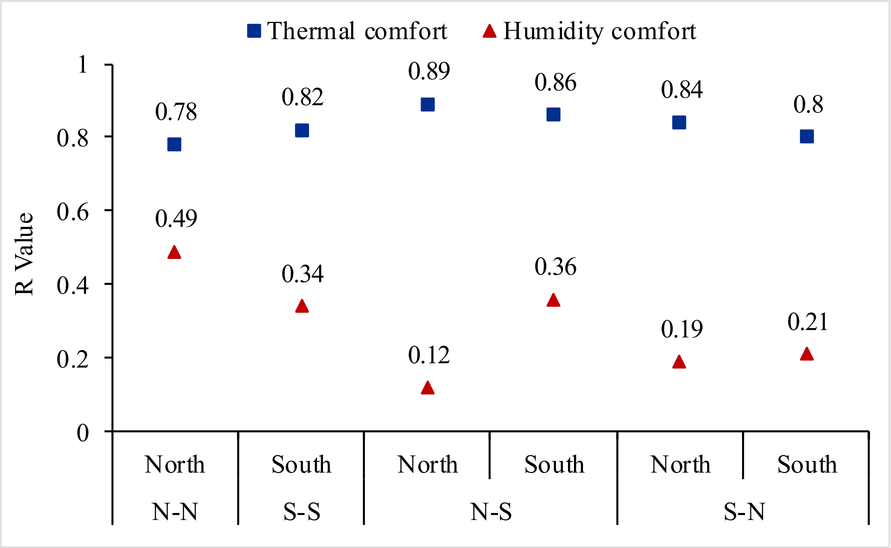

Figure 12 Correlation between thermal/humidity comfort and overall satisfaction

4 Discussion

4.1 The asymmetry of thermal adaptation

Thermal comfort adaptation theory encompasses the idea that people's perception of thermal comfort is influenced by what kinds of thermal environments they have been exposed to. The comparison between group N-N and group S-S in this current study offers some insights on this hypothesis. Group N-N lived in what would be considered a 'higher-grade' winter indoor climate (i.e., it was heated), and the majority of them (57%) expressed neutral thermal sensations, with the remainder roughly divided between warm and cold sensations. This was in stark contrast to group S-S, who lived in southern China without district heating, and 74% expressed cold thermal sensations, and only 23% neutral. In spite of these differences in thermal sensations, however, there were much smaller differences in comfort perceptions of these two groups (71% comfortable for N-N and 60% for S-S). One explanation for this phenomenon is that the S-S group was thermally adapted to these cooler sensations [33,34].

But, this was not the whole story. Another possible explanation might be the elevated thermal expectations of the N-N group. Table 6 shows that, compared with group S-S, the N-N group had a higher uncomfortable rate for almost every thermal sensation category. This suggests that northerners had become increasingly "fussy" about their thermal environment, compared to their southern counterparts who lived in environments with much colder temperatures.

If people with higher thermal expectation and their counterparts with lower expectation, can both be thermally satisfied, how should this convergence be achieved? Should one improve the quality of the indoor thermal environment which the lower expectation group is exposed to, or should one try to lower the expectation of those who have been 'spoiled' by thermal excellence? In other words, which trajectory is the easier or might simultaneously lead to reductions in energy use? The comparison between the migrating N-S and S-N groups in the current study suggest that it is much easier to raise one's expectation by providing better thermal environment than it is to persuade those who expected indoor thermal excellence to reduce their expectations and adapt to lower-grade indoor thermal environments. Specifically, both N-S and S-N groups considered winter indoor climate in northern China were more neutral and comfortable than those in southern areas. Apparently, it was easier for the S-N group migrating from environments of lesser quality to indoor climatic excellence, than for the N-S group who migrated in the opposite direction. However, this can also have enormous consequences for increased energy consumption and the risks of climate change.

In the behavioral economy research field, there is a notion called "endowment effect", which describes the tendency for people who own a particular good to value it more than people who do not [35]. Usually, the endowment effect can be attributed to people's loss aversion, which assumes the psychological impact of a loss is greater than an equivalent gain [36]. Under the context of this current study, if we consider the indoor thermal environment as a type of good, it can be seen that building occupants' thermal comfort expectations of the indoor thermal environment can be subject to this loss aversion assumption as well. Migrating from a higher indoor thermal environmental quality to places of lesser indoor thermal environment quality (i.e, the N-S group), the thermal comfort effects are overwhelmingly negative. On the flip-side, migrating from a lesser indoor thermal environmental quality to places of higher indoor thermal environment quality (i.e., the S-N group), the thermal comfort benefits are overwhelmingly positive. Even for the humidity perception, both N-S and S-N groups expressed significant negative feedback on humidity comfort perception when they migrated from one kind of lower-grade indoor humidity environmental to another type of lower-grade indoor humidity environment.

4.2 Practical implication

The current study sheds some light on the fact that people's understanding of thermal comfort is, indeed, malleable and is ultimately a subjective state of mind that depends on not only on the physical thermal environments but also social and cultural expectations. People in higher quality thermal environments have been shown to adapt to thermal homogeneity if that is what they expect to have (as for the N-N group). Alternatively, people can also adapt to a more variable indoor climate if that is what they are exposed to repeatedly (as for the S-S group). This phenomenon suggests that building occupants' thermal comfort perception is closely related to their thermal experience, and we believe that comfort expectation plays a factor.

The malleable nature of thermal comfort expectation suggests one might consider alternative policy approaches besides always aiming to build or retrofit buildings with tightly controlled indoor thermal environments. But this approach requires us to rethink how we define the way to provide thermal comfort for building occupants since our current standards and design practices have more typically denied opportunities for occupants to control their own environments to cope with their individual preferences. For example, the current comfort standards like ISO7730 require indoor thermal environments be tightly controlled around a theoretical optimum by minimizing temporal and spatial fluctuation ranges. Such stringent requirements of indoor thermal environments will undoubtedly shift occupants' perceptions of thermal comfort in the long-term.

Moving forward, we need to advocate for greater flexibility in comfort strategies [37,38]. To some extent, the adaptive comfort model has made efforts to encourage occupants' adaptive behaviors in the context of naturally ventilated buildings, but there are so many more potential applications. It has been discovered that greater degrees of personal environmental control have positive impacts through both psychological and behavioral adaptive approaches, which could enhance occupants' satisfaction with their indoor thermal environment. If the building's HVAC systems could be running in a "part-time & part-space" mode depending on the occupants' individual needs, instead of the "whole-time & whole-space" mode prevalent in many buildings today, energy use could also be reduced. Currently, there is an ongoing IEA-EBC (International Energy Agency - Energy in Buildings and Communities) Annex 69 project [39], which is entitled "Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings" and involves thermal comfort researcher participants from around the world. The aims of Annex 69 are to develop and improve the adaptive method in indoor thermal environment standards, and to propose guidelines for using the adaptive approach in low energy building design, operation, refurbishment, and new personal thermal comfort systems [40].

4.3 Limitations and future challenges

The current study is based on a general online survey, and no physical thermal parameters were measured. The issues of adaptation and migration could be further explored through well-designed field studies which combine physical measurements are "right now" surveys (i.e., rather than general thermal impressions). Especially for the demand factor (Equation 2), it can be defined as in sum of uncomfortable percentage throughout a certain temperature range instead of 7-points thermal sensation votes. In this way, more solid conclusions can be drawn with more detailed observations of actual thermal conditions, occupants' activity levels and clothing insulation, personal control activities, etc.

5 Conclusions

This study investigated the relationships between occupants' indoor thermal experience and their thermal comfort perception. The following findings and suggestions emerged: (1) People's understandings of thermal comfort are mutually dependent on their indoor thermal experiences. Long-term comfortable thermal experiences can raise occupants' thermal expectation, while lower-grade non-neutral thermal environment can bring about thermal adaptation. (2) Building thermal comfort expectations exhibit asymmetric dynamics. It is easier and quicker for occupants to get accustomed to the thermally neutral lifestyle than it is for 'spoiled' occupants to lower their expectations and adapt to non-neutral indoor climate. (3) It is necessary to review the indoor environmental quality assessment in current standards – their tight requirements may not necessarily produce thermal comfort satisfaction. More flexible approaches and new comfort strategies should be encouraged.

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