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Thermal adaptation in built environment – a literature review, discussion and primary exploration

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Abstract

Research into thermal adaptation in built environment first began in the mid-70's in response to the oil-shocks and has recently regained attentions due to increasing concerns of human impacts on both energy consumption and global climate change. Thermal adaptive models, climate chamber and field studies for adaptation were reviewed in the present paper and the gaps between theoretical and experimental studies in the field of thermal adaptation in built environment were found through discussions on feedback loop, adaptive factors, climate chamber and field evidences. A new research framework and method were proposed to fill the gaps and validated in a series of studies in naturally ventilated buildings in hot-humid area of China. The adaptive evidences for behavioral adjustments, physiological acclimatization and psychological adaptations were obtained, which indicates that the new research framework and method are effective in the discovery of inner mechanisms of human thermal adaptation in built environment.

Keywords: Thermal adaptation, thermal adaptive model, field study, climate chamber study

1 INTRODUCTION

Research into thermal adaptation in built environment first began in the mid-70's in response to the oil-shocks and has recently regained attentions due to increasing concerns of human impacts on both energy consumption and global climate change. Lots of thermal comfort field studies were conducted throughout the world and several thermal adaptive models were proposed to rationally explain the differences between field and climate chamber studies. The final goal of the studies on thermal adaptation is to fully discover inner mechanisms of thermal adaptation and accurately predicate human thermal responses in actual built environments. The present paper reviewed literature, discussed the existing gaps between theoretical and experimental studies, and proposed and validated a new research framework and method.

2 OVERVIEW

2.1 Thermal adaptive models

Thermal adaptive models, which are to explain the findings of experimental studies, reveal the inner mechanisms and establish the basic equations applicable to all observations, are *the most important signs* of studies on thermal adaptation in built environment. Three models proposed by *Brager and de Dear* (Brager and de Dear 1998), *Nicol and Humphreys* (Nicol and Humphreys 2001) and *Fanger and Toftum* (Fanger and Toftum 2001) represent the prevailing ideas and insights in the field of thermal adaptive model studies.

Brager and de Dear (Brager and de Dear 1998) proposed a thermal adaptive model in built environment in a systematic way, in which thermal adaptation was divided into three modes: *behavioral adjustment, physiological acclimatization and psychological adaptation*. The impacts of physiological acclimatization were denied and the impacts of behavioral adjustment and psychological adaptation were validated through literature review, and thermal experiences (history) on past exposure and perceived control on current exposure were supposed to be the most important factors shaping thermal expectation and psychological adaptation in their model. Nicol and Humphreys (Nicol and Humphreys 2001) viewed thermal adaptation as the result of a feedback between the comfort of the subjects and their *behaviour*. Fanger and Toftum (Fanger and Toftum 2001) proposed an expectancy factor to modify the PMV model, in which *thermal expectation* was considered as the right adaptive factor.

2.2 Climate chamber studies for adaptation

Thermal adaptation is effective in climate chambers, in different levels or extents but with the same affecting ways on human responses as that in actual buildings. Climate chamber studies can provide useful evidences for thermal adaptation due to their rigid controlled conditions, accurate physiological measurements and high degrees of reproducibility.

Brager and de Dear (Brager and de Dear 1998) are the first to collect climate chamber studies and obtain climate evidences for adaptation. The collected studies were performed on the subjects from various climates and living or working conditions (see Table 1), which were believed to shape the different acclimatization backgrounds of the subjects. Based on their evidences, they suggested that the slower process of acclimatization was not so relevant to thermal adaptation in the relatively moderate conditions found in buildings, and discomfort and thermal acceptability of resting or lightly active occupants in their residences and office buildings were not affected by physiological process of acclimatization.

Table 1 The climate chamber studies for adaptation collected by Brager and de Dear

No.	Subjects	Place	Experimental method	Ref.
1	Danish college students	Demark	2	(Fanger and Langkilde 1975)
2	Danish winter swimmers	Demark	2	(Fanger et al. 1977)
3	Danish meat packers from a refrigerated storeroom	Demark	2	(Fanger et al. 1977)
4	Long-term inhabitants of the tropics	Demark	2	(Fanger 1972)
5	Singaporean college students	Singapore	2	(de Dear et al.

				1991)
6	Chinese college students in Hong Kong	Hong Kong	1	(Chung and Tong 1990)
7	American people	US	1	(Gonzalez 1979)

Note: Experimental method 1 means the method of testing under constant conditions, and experimental method 2 means the preferred temperature method.

2.3 Field studies for adaptation

Field studies are the *essential sources* of thermal adaptive studies due to their riches in real world settings, human interactions with environment and various adaptive opportunities. The differences in human responses between field studies and climate chamber studies or the heat balance models are *the strongest evidences for adaptation*.

Humphreys (Humphreys 1976) first systematically collected thermal comfort field studies for adaptation. Those studies are mainly based on simple measurements of indoor temperature and possibly humidity at one height, which was labeled as Class III and considered not suitable for explanatory analysis of thermal adaptation by Brager and de Dear (Brager and de Dear 1998). *de Dear and Brager* (de Dear 1998; de Dear and Brager 1998) conducted the second systematic collections in 1998 in the ASHRAE RP-884 project, in which most of Class II and I studies (all the environmental and personal variables necessary as inputs to the heat balance models were measured) published before were collected and a open-to-public database was established with sample scale of nearly 21000.

A rough statistic on Class II and I field studies published thereafter was performed by the authors through extensive literature review. The published paper number (including journal and conference papers) outside of China is 22, including three large-scale surveys in Europe (McCartne and Nicol 2002), Japan (Goto et al. 2007) and Iran (Heidari and Sharples 2001), and 19 relatively small-scale surveys in Indonesia (Feriadi and Wong 2004; Karyono 2000), Libya (Ealiwa et al. 2001), Brazil (de Paula Xavier and Lamberts 2001), Singapore (Wong and Khoo 2003; Wong et al. 2002), US (Brager et al. 2004), Tunis (Bouden and Ghrab 2005), Germany (Wagner et al. 2007), Italy (Buratti and Ricciardi 2009; Corgnati et al. 2009; Corgnati et al. 2007), Nigeria (Ogbonna and Harris 2008), Malaysia (Dahlan et al. 2008), France (Moujalled et al. 2008), Israel (Becker and Paciuk 2009), Kuwait (Al-ajmi and Loveday 2010) and India (Indraganti 2010; Indraganti and Rao 2010), and the total sample scale is 57056.

The field studies in China started lately in 1999 (Xia et al. 1999) and came to prosperity in 2007 with 7 papers published and the total paper number is 32, including two surveys in Hong Kong (Mui and Chan 2003; Wong et al. 2009), three surveys in Taiwan (Cheng et al. 2008; Hwang et al. 2009; Hwang et al. 2006) and 27 surveys in mainland (Cao et al. 2008; Han et al. 2009; Hana et al. 2007; Ji and Dai 2005; Jiang et al. 2005; Wang et al. 2003; Wang 2005; Zhang et al. 2007) (about 60% of the papers are in Chinese and only papers in English is listed in the reference), and the total sample scale is 18471.

The studies outside of China cover all the inhabitable continents of the world and a wide range of climates from tropical to temperate zones (see Figure 1). Totally 300 buildings were investigated, including naturally ventilated, air-conditioned or mix-mode offices, dwellings and classrooms. The studies in China cover the most developed regions and tropical, subtropical and temperate monsoon zones (see Figure 2). Nearly 118 buildings were surveyed in China and most of them are residential and educational buildings without air-conditioning devices or systems.

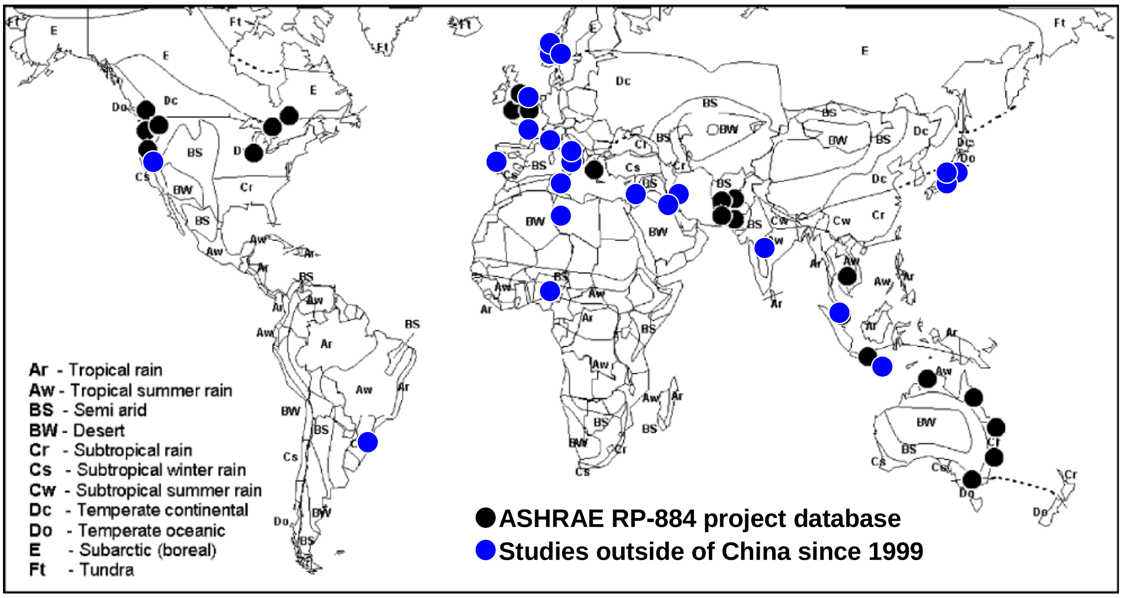


Figure 1 The climatic distribution of the field studies outside of China (Zhang and Zhao 2010)

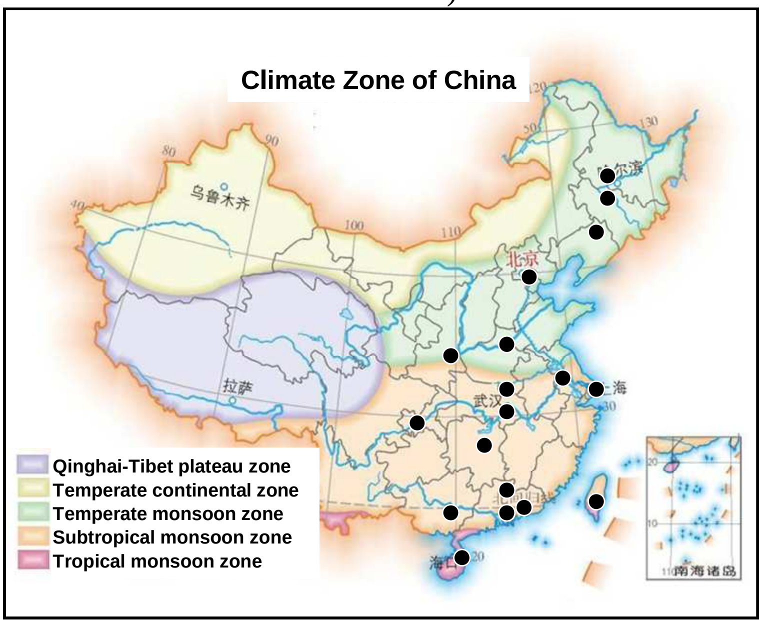


Figure 2 The climatic distribution of the field studies in China (Zhang and Zhao 2010)

3 GAPS BETWEEN THEORETICAL AND EXPERIMENTAL STUDIES

In general, theoretical studies are to reveal inner mechanisms and provide explanations for experimental studies, and experimental studies are to supply new findings in observation and validations for theoretical studies. In the field of thermal adaptation in built environment, thermal adaptive models and their key adaptive factors were considered as theoretical studies and climate chamber and field studies for adaptation as experimental studies. In the light of literature review, the gaps between theoretical and experimental studies were found through the following discussions.

3.1 Feedback loop

Feedback loop is a common feature of all the adaptive models, and detailed descriptions of feedback loops for adaptation including their driving and functioning processes are very important for the understanding of cause-and-effect relationships underlying thermal adaptation. All related information on feedback loop from the existing models was collected as followings.

1. In the adaptive view of thermal comfort, however, behavioral adjustment represents an immediate and conscious feedback link, where *the sense of discomfort or dissatisfaction is not only the outcome but also serves as the starting point* (Brager and de Dear 1998).
2. Behavioral adjustment includes all modifications a person might consciously, or unconsciously make, which in turn *modify heat and mass fluxes governing the body's thermal balanc*e (Brager and de Dear 1998).
3. Nicol and Humphreys (1973) first suggested that this effect could be the result of a *feedback between the comfort of the subjects and their behavior* and that they 'adapted' to the climatic conditions in which the field study was conducted (Nicol and Humphreys 2001).
4. Physiological acclimatization is mediated by the autonomic nervous system and *directly affects the physiological thermoregulation setpoints* (Brager and de Dear 1998).
5. Psychological adaptation encompasses the effects of cognitive and cultural variables and describes the extent to which habituation and expectation *alter one's perception of and reaction to sensory information* (Brager and de Dear 1998).

It can be seen that the current picture on feedback loops of thermal adaptation is not clear and completed due to the unknown starting points for physiological acclimatization and psychological adaptation and the uncompleted descriptions on all feedback loop processes, which produces an unclear theoretical framework and results in that the experimental studies for quantifying feedback loop are unable to be carried out and the explanations for observations are kept in a conceptual and qualitative stage.

3.2 Adaptive factors

In the Brager and de Dear's model, *thermal exposure and experience* are proposed to be the key factors for physiological and psychological adaptation. However, the model only provides *conceptual descriptions* instead of quantitative definitions for the factors, which to a large extent results in the confusions on their indicators. Various indoor or outdoor climate indices were chosen as the indicators by researchers and monthly mean (ASHRAE 2004) or exponentially weighted running mean (CEN 2007) of outdoor air temperature were used in the existing thermal comfort standards.

In the Fanger and Toftum's model, the *expectancy factor* is the key adaptive factor and a table is provided for its estimation. However, the two important parameters in the table, which are the duration of the warm weather over the year and whether such buildings can be compared with many others in the region that are air-conditioned, are *qualitative* in their definitions and difficult to be used in a quantitative and consistent way. That the key adaptive factors are not proposed in a quantitative way can be a big obstacle for the validations and applications of the thermal adaptive models.

3.3 Climate chamber evidences

The collection of climate chamber studies is not fully completed and the evidences are not reasonably illustrated in the study by Brager and de Dear due to the following reasons. Firstly, not only the change of climates and living or working conditions, but also the change of *seasons* may be the important sources for acclimatization. Secondly, the effects of thermal adaptation on human responses occur not only in optimal conditions, but also in *warm or cold* conditions maybe in a more evident way. Thirdly, all the factors shaping acclimatization backgrounds, such as climate, season, living or working condition, can affect *thermal experiences* as well, which would in turn influence subjects' human responses and change the implications of evidences.

The existing climate chamber evidences are not sufficient and more studies conducted in warm or cold conditions are needed to be well collected and systematically analyzed in terms of climates, living or working conditions and seasons, which will provide evidences for both physiological and psychological adaptations.

3.4 Field evidences

The field evidences for adaptation in literature can be divided into three classes. Class A is in a form of neutral temperature and acceptable temperature range, which are derived from linear relationships between thermal sensation and *indoor climate index*. Class B is in a form of linear relationships between indoor neutral temperature and *outdoor climate index*. The evidences of Class A and B are both established through comparisons of the field observations with the predictions by the PMV model or between building types, seasons or climates. Class C is in a form of relationships between *adaptive behaviour* and indoor or outdoor climate index.

The meanings of the field evidences are highly depended on the selection of indoor or outdoor climate index. The often adopted indoor climate indices can be divided into *simple indices* (air temperature, operative temperature, global temperature or ET*) and *integrated indices* (PMV or SET*) in terms of whether or not including all the known environmental and personal variables influencing thermal sensation. Simple indices were most often adopted in literature due to their clear physical meanings, fully developed measuring techniques and conveniences for direct practical applications. However, simple indices may not fully represent all characteristics of indoor climate and the evidences with simple indices may be not convincing.

Taking a field study in naturally ventilated buildings conducted by the authors as an example, air temperature was selected as the indoor climate index and accordingly a relationship between thermal sensation and air temperature was obtained. However, the other variables influencing thermal sensation, such as relative humidity or air velocity, varied greatly between or within data groups (see Table 2), which makes the meaning and the applicable range of the relationship unclear. Under such a circumstance, the comparison between the field results and the PMV model would be uncompleted and too weak to be an evidence for adaptation.

Table 2 Variation of variables while grouping with air temperature (Zhang et al.)

Variables	Maximum variation between groups	Maximum standard deviation within group
Relative humidity	51.48%	15.37
Air velocity	0.99m/s	0.56
Mean radiant temperature	17.23ºC	2.43
Clothing insulation	0.61clo	0.30

The most frequently adopted outdoor climate indices are monthly mean outdoor air temperature and ET*, which are obviously not enough to represent all the characteristics of outdoor climate related to thermal adaptation. More factors such as rainfall, wind speed and direction were tested as possible outdoor climate indices in the window opening behavior study by Haldi and Robinson (Haldi and Robinson 2009). The proper outdoor climate index is unnecessarily same for all modes of thermal adaptations due to their different feedback loop processes.

4 PRIMARY RESULTS OF A NEW EXPLORATION

4.1 A New research framework

Sense of discomfort, which has been widely accepted to be the strongest drive for human's thermal adaptation, was therefore supposed to be the common starting point of feedback loops for all modes of thermal adaptation. *The heat balance models* were considered as the known human relationship with environment. A sketch of feedback loops for thermal adaptation was drawn accordingly and shown in Figure 3. The sketch provides all shaping and functioning ways for all modes of thermal adaptation and can represent all the known adaptive models. Loop 1 represents the Nicol and Humphreys's model, loop 3 represents the Fanger and Toftum's model and loop 1 and 3 together represent Brager and de Dear's model.

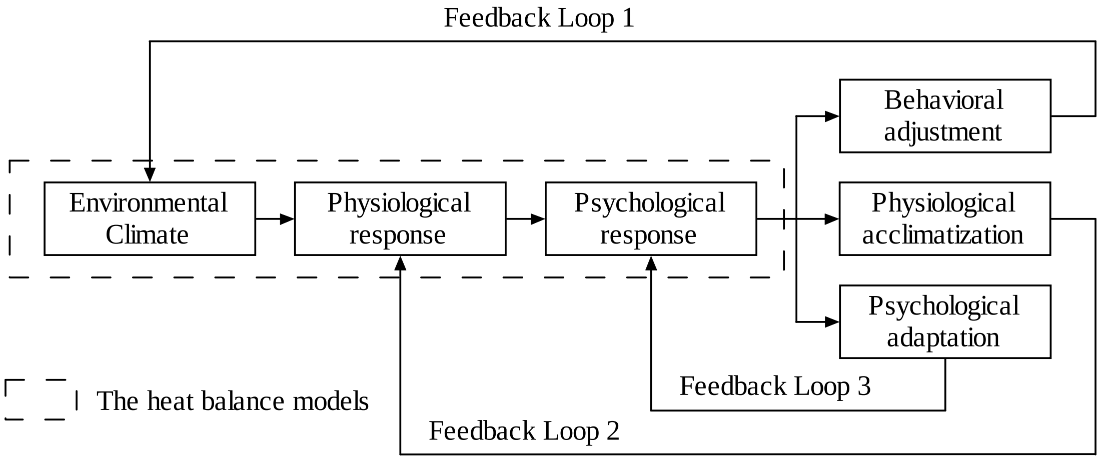


Figure 3 Sketch of feedback loops for thermal adaptation

Based on Figure 3, the connections between theoretical and experimental studies in the field of thermal adaptation in built environment were established as shown in Figure 4.

The effects of behavioral adjustment can be studied and obtained in a quantitative way by direct adaptive behavioral observations in various people, climates or building types. Comparison of climate chamber studies conducted in a cross-section of climates or seasons can provide evidences for the integrated effects of physiological and psychological adaptations.

While viewing the PMV model from the point of the adaptive model instead of the heat balance model, the subjects involved in the experimental studies on which the PMV model was based are different with those in the field studies to be compared in terms of past thermal exposure, experience and perceived control. Therefore, the comparisons between field studies and PMV provide evidences not sole for psychological adaptation, but for the integrated effects of physiological and psychological adaptations, which is suitable as well for naturally ventilated vs air conditioned buildings.

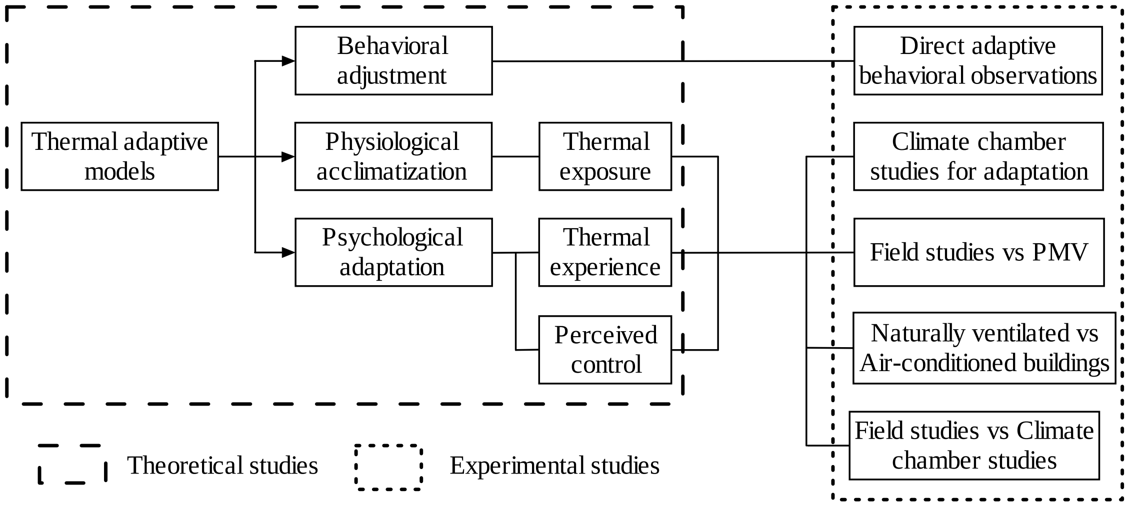


Figure 4 The connections between theoretical and experimental studies in the field of thermal adaptation in built environment (Zhang and Zhao 2010)

4.2 Research methods

It can be seen from Figure 4 that the existing research methods and their generated adaptive evidences are unable to effectively separate the impacts of each mode of thermal adaptation on human responses. The research method proposed by Oseland (Oseland 1995), in which *the same group of subjects are recruited for both field and climate chamber studies*, was adopted and well extended by the authors for the purpose of separating the impacts on human responses for each mode of thermal adaptation by utilizations of the advantages of field and climate chamber studies and their differences.

The extensions of the research method included:

1. The field study is performed for *a whole year* and the climate chamber study is conducted in a cross-section of *seasons*, which can provide more information on thermal adaptation.
2. Both the environments and subjects are kept in their *actual status* in the field study and *integrated indices* are used as indoor index in the comparisons of field and climate chamber studies.
3. *Physiological* responses are accurately measured in the climate chamber study, which can directly provide information on physiological acclimatization.

4.3 A new exploration

The authors attempted to validate the new research framework and the extended research method through a new exploration on thermal adaptation in naturally ventilated (NV) buildings in hot-humid area in China.

Thirty healthy college students were recruited in the study, who were born and grew up in the Pearl River Delta (a typical hot-humid area in China) and have recently lived and studied for more than three years in NV buildings in a university campus in Guangzhou (a typical city in hot-humid area of China), which makes them representative of local inhabitants long-time living in NV buildings in hot-humid area of China.

The NV buildings most frequently occupied by the subjects were investigated, which includes a teaching building, a drawing building and several dormitory buildings (see Figure 5a-c). Air temperature, relative humidity, globe temperature and air velocity were measured by using the laboratory-grade instruments (Figure 5d) according to ISO 7726 (ISO 1998) at three heights. The field study was carried out for a whole year from May 2008 to May 2009 and totally 23 weeks and 921 sets of raw data were collected.

a Classroom building

b Drawing building

c Dormitory building

d Devices for physical measurements

Figure 5 The buildings and devices in the field study (Chen et al. 2010a)

During the period of the field study, two climate chamber studies were performed on these subjects in summer and winter respectively. The experimental methods were kept the same with Fanger’s classics study (Fanger 1970) and the test conditions were designed to be in a wide range from cool to warm. A climate chamber in South China

University of Technology was used and skin temperature, sweating and heart rate were measured as shown in Figure 6.

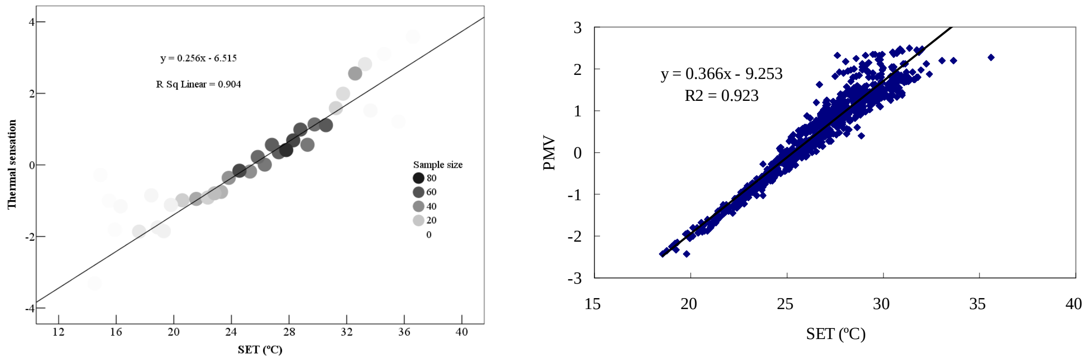
a Climate chamber b Physiological measurements

Figure 6 The climate chamber and physiological measurements in the climate chamber study (Chen et al. 2010b)

4.4 Field evidences based on an integrated index

Taking SET as an indoor climate index, a good linear relationship between thermal sensation and SET was obtained (see Figure 7a). Thermal sensation (TS) was further expressed as a function of PMV based on the relationship between SET and PMV (see Figure 7b):

TS = 0.7PMV - 0.04 (1)



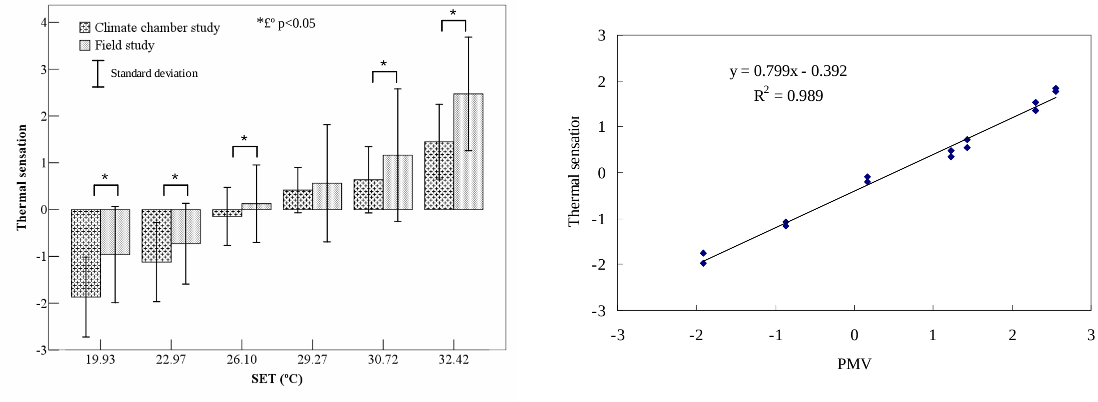
a Thermal sensation as a function of SET b PMV as a function of SET

Figure 7 Field evidences based on an integrated index (Zhang et al. 2010a)

The constant of Eq. (11) can be reasonably ignored as it is close to zero, which indicates that the modified PMV model proposed by Fanger and Toftum (Fanger and Toftum 2001) is proved to be suitable for the field investigations and the expectancy factor for the subjects involved in the present study is 0.7. Equation (1) provides a key *evidence for physiological and psychological adaptations* while considering the impacts of behavioral adjustment can be fully accounted for by the PMV model.

4.5 Psychological adaptation

Perceived control and its impact on thermal expectation were proposed by Brager and de Dear to explain the difference between field and climate chamber studies (Brager and de Dear 1998). In the present study significant differences were found between the actual buildings and the climate chamber on the thermal sensations reported by the same group of subjects (see Figure 8a), which provides a direct *evidence for psychological adaptation driven by perceived control.*



a Comparisons between the field and climate chamber study

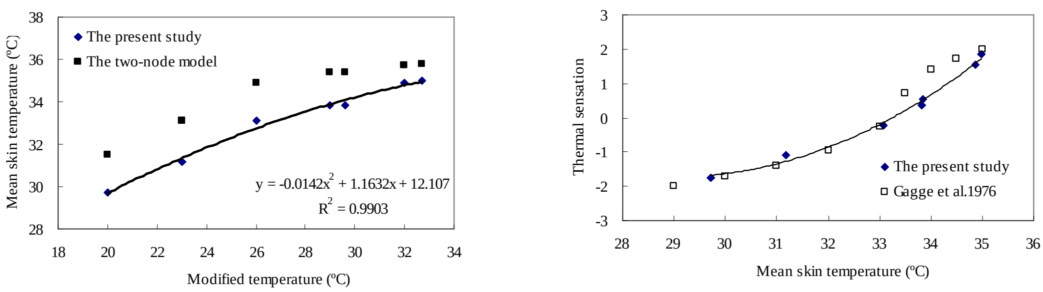
b Relationships obtained in the climate chamber

Figure 8 Psychological responses in the climate chamber study

The relationship between thermal sensation and PMV was established for the two climate chamber studies (see Figure 8b) and it was found that PMV overestimated the sensations of the subjects, which could be further explained by physiological or psychological adaptations.

4.6 Climatic adaptation

The two-node model was established by Gagge et al. (Gagge et al. 1971) based on the results from US and Europe (mainly at temperate zone). It was found that the two-node model overestimated the mean skin temperature of the subjects in the present study and the biggest difference closed to 2ºC (see Figure 9a), which provides a direct *evidence for physiological acclimatization*.



a Comparisons in mean skin temperatures

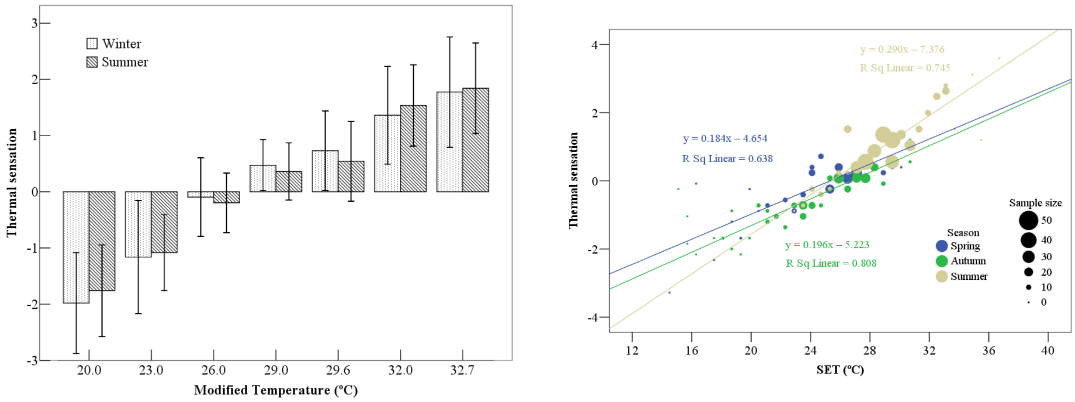
b Comparisons in relationships between thermal sensation and mean skin temperature

Figure 9 Effects of outdoor climate on physiological responses (Chen et al. 2010c)

Gagge et al. (Gagge et al. 1967) investigated the relationship between thermal sensation and mean skin temperature in a climate chamber. Comparing the results obtained by Gagge et al. and the present study, it was found that the relationship was kept almost unchanged (see Figure 9b), which indicates that the differences on skin temperatures and physiological acclimatization can explain to a large extent the differences between thermal sensation votes and PMV in Figure 8a, and the impacts of thermal experience can be reasonably ignored.

4.7 Seasonal adaptation

Figure 10 shows the seasonal change of thermal sensation in the climate chamber study and the field study. For all the experimental conditions in the climate chamber and the most conditions in the surveyed NV buildings, no significant seasonal variations on the subjects' thermal sensations were found, which indicates that the impacts of *seasonal physiological and psychological adaptations* can be ignored.

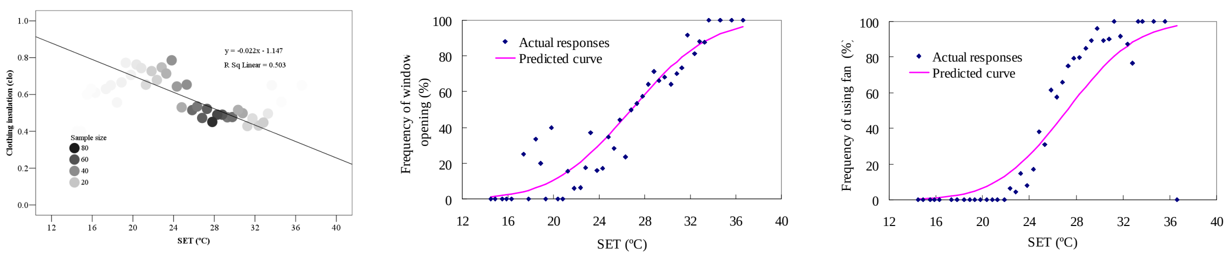


a Climate chamber studies b Field studies

Figure 10 Seasonal change of thermal sensation (Zhang et al. 2010a, 2010b)

4.8 Behavioral adjustment

The most common adaptive behaviours were found to be clothing adjustment, window opening and using fans in the field study and their relationships with SET are shown in Figure 11, which are the direct *evidences for behavioral adjustment*.



a Clothing insulation b Window opening frequency c Fan using frequency

Figure 11 Relationships between adaptive behaviours and SET (Zhang et al. 2010a)

4.9 Summary

The adaptive evidences and the impacts on human responses can be effectively separated and obtained for each mode of thermal adaptation by using the new research framework and method. For the people long-time living in NV buildings in hot-humid area of China, behavioral adjustment, climatic physiological acclimatization and psychological adaptation driven by perceived control are their main adaptive ways, and seasonal adaptations are yet not significant. Behavioral adjustment is the most powerful way for the people to maintain their comfort by control of environment instead of human relationship with environment. Climatic physiological acclimatization shaped during a long-time living contributes to the adaptive change of human relationship with environment more than psychological adaptation driven by perceived control.

5 CONCLUSIONS

A literature review, discussion and primary exploration of thermal adaptation in built environment are presented in the present paper and the following conclusions can be drawn.

1. A good many thermal comfort field studies for adaptation have been widely performed throughout the world and covers a wide range of climates from tropical to temperate zones, and the total sample scale of the studies approaches 96000.
2. There are gaps between theoretical and experimental studies in the field of thermal adaptation in built environment due the unclear picture of feedback loops, the conceptual and qualitative descriptions on adaptive factors, the uncompleted collection and illustration on climate chamber evidences and the problems with indoor and outdoor indices in field evidences.
3. Compared with simple indices, integrated indices would have the advantages on their clearer meanings, wider applicable ranges for the obtained results and more completed comparisons with the PMV model.
4. A new research framework was proposed based on the completed descriptions of feedback loop processes and the combinations of thermal adaptive and heat balance models, which was testified to be an effective approach to discover inner mechanisms of human thermal adaptation in built environment.
5. For the people living in naturally ventilated buildings in hot-humid area of China, behavioral adjustment, climatic physiological acclimatization and psychological adaptation driven by perceived control are their main adaptive modes.

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