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DISSERTATION

Assessment of thermal comfort under transitional conditions

ausgeführt zum Zwecke der Erlangung des akademischen Grades einer Doktorin der technischen Wissenschaften unter der Leitung von

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Kurzfassung

Thermische Behaglichkeit dient dazu, angenehme Bedingungen für die Raumnutzer in einer gegebenen Umgebung zu ermitteln. Die typische Standards für thermische Behaglichkeit orientieren sich dabei aber an Laborstudien an thermisch angepassten Individuen in sitzender Position. Dieser Ansatz eines stationären Zustandes spiegelt jedoch selten die wahren Begebenheiten in einem Gebäude wieder. Darüber hinaus werden schrittweise Veränderungen der Umwelt oder Umgebungen mit wenig Zeit zur Anpassung nicht ausreichend berücksichtigt.

Diese Arbeit behandelt die Beurteilung thermischer Behaglichkeit in Test-Übergangszuständen. Gruppen von Testpersonen bewegten sich in einem Labor durch mehrere Räume mit unterschiedlichen thermischen Bedingungen. Die thermische Behaglichkeit der Teilnehmer wurde vor dem Übertritt, unmittelbar nach dem räumlichen Übertritt sowie nach einer Anpassungsphase ermittelt. Das Hauptaugenmerk der Studie lag dabei auf dem Vergleich der Beurteilungen thermischer Behaglichkeit unmittelbar nach dem räumlichen Übertritt mit jenen von bereits angepassten Testpersonen. In Übergangszuständen drückte dabei ein größerer Anteil der Testpersonen Zufriedenheit (Thermal Comfort Vote) aus, verglichen mit den Testpersonen in stationären Zuständen. Im Vergleich zu den Experimenten im Frühling, wurde in den Winterexperimenten eine eine geringere Temperaturtoleranz gegenüber den akzeptablen thermischen Innenbedingungen festgestellt, sowohl vor als auch nach Anpassung. Bemerkt wurde auch, dass die Teilnehmer empfindlicher gegenüber einem Übergang in Richtung der neutrality temperature reagierten als wenn sie sich davon davon entfernten.

Die Ergebnisse deuten darauf hin, dass die Unterschiede im Thermal Sensation Vote (TSV) unmittelbar nach einem Übertritt mit den jeweiligen Temperaturunterschieden übereinstimmen. Die Veränderung des Thermal Comfort Vote (TCV) unmittelbar nach dem räumlichen Übertritt folgt diesem Muster allerdings nicht auf konsistente Weise. In dieser Studie wurde vielmehr eine Übereinstimmung mit der neu eingeführten „thermischen Distanz“ zweier Räume gefunden, diese entspricht der effektiven Temperaturdifferenz ($\Delta\theta_{eff}$).

Keywords: Thermische Behaglichkeit; thermisches Empfinden; räumlicher Übertritt; effektive Temperaturdifferenz

Abstract

Thermal comfort is designed to determine thermally comfortable conditions for occupants in a given environment. The typical thermal comfort standards were geared toward thermally adapted individuals in a sedentary position based on laboratory studies. However, this steady state approach does not reflect the most frequent experiences in a building. Moreover, environmental step-changes or spaces where there isn't enough time to stay for adaptation would not be accounted for appropriately.

This thesis explores thermal comfort assessments in transitional states. Multiple groups of participants moved in a laboratory through a number of spaces with different thermal conditions. The thermal sensation and comfort evaluations of the participants were assessed before transition, immediately after the spatial transition, and after a short period of adaptation. The main objective of the study was to compare participants' thermal comfort assessments immediately after a spatial transition with those of thermally adapted participants. A larger percentage of occupants expressed satisfaction (Thermal Comfort Vote) in transitional states than in steady states. Moreover, a narrower tolerance range in thermally acceptable indoor conditions, for both before and after adapted situations, was found in the winter than in the spring experiments. Participants were found to be more sensitive to moving through a transition involving thermal experience toward neutrality, particular involving a lower temperature, than going through a transition involving thermally experience away from neutrality.

The results suggest that the change in people's expressed Thermal Sensation Vote (TSV) immediately after a spatial transition is consistent with the respective temperature difference. The change in Thermal Comfort Vote (TCV) immediately after a spatial transition, however, did not consistently follow the temperature difference pattern. Rather, it was found to be consistent with a proposed new measure of the "thermal distance" between the two rooms, namely the effective temperature difference ($\Delta\theta_{eff}$).

Keywords: Thermal comfort; thermal sensation; spatial transition; effective temperature difference

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Abbreviations

Acronym	Meaning
TSV	Thermal sensation vote
TCV	Thermal comfort vote
TPV	Thermal preference vote
PMV	Predicted mean vote
PPD	Predicted percentage of dissatisfied
EPS	Expanded polystyrene
Av.	Average
S. D.	Standard deviation
Max.	Maximum
Min.	Minimum

Symbol	Meaning	Units
A_{du}	Dubious area	m^2
C_{res}	Respiratory convective heat exchange	$W.m^{-2}$
CO_2	Carbon dioxide	ppm
E_c	Evaporative heat exchange at the skin	$W.m^{-2}$
E_{res}	Respiratory evaporative heat exchange	$W.m^{-2}$
f_{cl}	Clothing area factor	-
H	Dry heat losses	$W.m^{-2}$
h_c	Convective heat transfer coefficient	$W.m^{-2}K^{-1}$
I_{cl}	Thermal resistance of clothing	clo, $m^2K.W^{-1}$
Il	Illuminance	lx
M	Metabolic rate	met, $W.m^{-2}$
p_a	Partial water vapor pressure	pa
rh	Relative humidity	%
t_a	Air temperature	ºC

t_{cl}	Surface temperature of clothing	ºC
t_r	Mean radiant temperature	ºC
v_a	Air velocity	$m.s^{-1}$
v_{ar}	Relative air velocity	$m.s^{-1}$
W	External work	$W.m^{-2}$
$\Delta\theta_{eff}$	Effective temperature difference	K

1 Introduction

1.1 Motivation

Thermal comfort has been an area of substantial research for more than four decades. The purpose of these studies is to develop comfortable thermal conditions for occupants in a given environment. Moreover, it is also important to find a balance between energy usage and an occupant’s actual needs in thermal-mechanically controlled buildings. Therefore, thermal comfort investigations provide not only comfortable and healthy spaces, but also determine the energy consumption of building environments.

Thermal comfort is generally defined by ASHREA Standard 55 (2004) as “*that condition of mind which expresses satisfaction with the thermal environment*”. Thus, thermal comfort is a perception that may be influenced by physical, physiological and psychological factors. Therefore subjective study is a valid way to achieve an overall evaluation involving individually reflected consciously integrated thermal comfort judgment interacted by the objective parameters of thermal environment and personal factor. Parsons (2003) mentioned thermal comfort perception may be predicted more accurately by air temperature than by thermoregulation in transitional conditions. Chen et al. (2011) and Gagge et al. (1967) researched thermal comfort on both thermal perception and skin and body temperatures of the participants which found the subjective thermal perception reached a neutral balance more quickly than the measured skin and body temperatures in the new thermal environment after a temperature change.

In the most well-known thermal comfort model, the Predicted Mean Vote (PMV) developed by Fanger (1970) on the basis of laboratory studies, the thermally adapted occupant is assumed to be comfortable when the heat exchange between the human body and the thermal environment is in thermal balance. However, this steady state approach *is not adequate to explain real life thermal comfort requirements because transient conditions are more likely to happen during a typical day* (Ugursal, 2010).

Thermally dynamic conditions may be produced by building envelope, heated or cooled settings in a space, climate, and occupancy behavior. Thus, steady state conditions are rarely encountered in practical situations. Madsen (1987) found indoor temperature fluctuations between 0.5 and 3.9 K depending on the constant set point of combinational heating and control system. Berglung and Gonzalez (1978) concluded that slow temperature ramps up to 0.5K/h were not significantly notable to the occupants and it could be seen as a steady environment. However, de Dear and Brager (1998) concluded that occupants in naturally ventilated buildings accept a wider temperature range than in a thermally constant environment. Arens et al. (2006) also observed the maximum of thermal comfort (very comfortable) responses can be achieved during transitional conditions but not in steady environments. With increased interest in thermally dynamic conditions, more and more researches have taken place on transitional spaces, i.e. buffer zones or semi-outdoor areas, located between two different thermal conditions as a component of a building (Pitts, 2013; Chun et al., 2004).

In addition, heating, ventilation, and air-conditioning technologies and systems are typically used to provide desirable indoor thermal environments for human occupancy. Each space is typically controlled as an independent environment (Heiselberg, 1999) depending on its specific usage. However, this has the potential to create greater thermal differences between spaces treated as isolated environments. If occupants go through spatial transitions involving noticeable temperature differences, typical thermal comfort evaluation schemes which are geared toward thermally adapted individuals (ASHRAE Standard 55, 2004; ISO 7730, 2005) may not apply (Jones and Ogawa, 1992). People are frequently exposed to such transitional states, for example some spaces such as a lobby, corridor and staircase in a building where the stay would only be for a short period. Or when they enter or exit a building or when they move through rooms with different temperatures within a building such as large public buildings, shopping malls and office buildings.

Current thermal comfort standards have so far evaluated for neither transitional spaces nor states involving an environmental step-change. However, research on thermal comfort during an environmental step-change so called transitional states would have potential to explain most transitional conditions. Nakano (2003) has suggested that thermal comfort conditions in transitional states may apply to, the two primary design requirements in a large-scale building, short-term phase spaces and environmental step-change states. Thermal comfort considerations within transitional conditions is significant for maintaining a continuously comfortable feeling of life (Raja and Virk, 2001; Hensen, 1990).

A disregard of thermal evaluation processes pertaining to transitional states may result in inappropriate temperature settings, inefficient thermal controls, and poor thermal comfort conditions. Thermal comfort in transitional states is considered in this thesis in order to provide a continuously thermally comfortable experience.

1.2 Objectives

Our specific objective is to investigate people's thermal sensation and comfort assessments as a consequence of moving through spaces with distinct thermal conditions. Specifically, thermal sensation vote (TSV) and thermal comfort vote (TCV) of thermally adapted people shall be captured before they moved from one space to another. The same votes were collected immediately after transition and following a brief period of thermal adaptation. The subjective expressions of thermal conditions shall be analyzed in the context of collected indoor environmental data (air temperature and relative humidity) during the experiments. The results shall be compared with calculations based on conventional thermal comfort models. Moreover, the collected data is processed to identify those variables that influence people's thermal sensation and comfort subsequent to a thermally relevant spatial transition.

To address the research objectives already outlined and obtain empirical data needed, the study was designed to address the following research questions:

- Do thermal sensation votes of thermally adapted participants in pre-transitional states agree with the predictions of standard (steady-state) thermal comfort models?

- Do thermal sensation votes of participants immediately after a spatial transition (involving temperature change) differ from the predictions of standard (steady-state) thermal comfort models, and if yes, to which extent?

- Do changes in thermal sensation and thermal comfort votes after moving from one room to another correlate with temperature difference between the two rooms?

- To which extent can post-transitional thermal comfort votes be predicted based on the temperature difference between the two rooms involved in the spatial transition?

The thesis is divided into six chapters. Chapter 1 outlines the motivations and the research objectives of this study. Chapter 2 includes some background information on the existing approaches for further investigating people's thermal sensation and comfort evaluations under transitional step-change conditions. Chapter 3 constructs the research method of the experiment designs for a laboratory study and a field study in the Museum of Art History (Kunsthistorisches Museum) in Vienna, Austria. Chapter 4 details the results of participants' thermal responses regarding environmental step-changes from the two independent studies, proposing a new measurement to predict their thermal perception in transitional states. Chapter 5 discusses the results and the research limitations of this study. Finally, chapter 6 draws conclusions on the study's results and its contribution to this field of research.

2 Background

According to Djongyang et al. (2010) there are rational and adaptive factors which influence thermal comfort sensation of occupants. The rational approach is that thermal comfort based on the heat exchange theory is influenced by several environmental and personal factors, providing appropriate thermal conditions to satisfy the majority of occupants in a steady state in a given space such as the most wide used PMV model (Fanger, 1970). While the adaptive approach includes factors that human behaviors and their expectations which could be adapted by culture and climate (Olesen and Parsons, 2002).

2.1 The rational approach

2.1.1 PMV and PPD

The Predicted Mean Vote (PMV) developed by Fanger (1970) is based on the principle of heat balance of the human body, between the generated heat within human body and the heat loss to the surrounding environment, built as the following relationship (Eq.1):

$$M - W = H + E_c + C_{res} + E_{res} \qquad \text{Eq. 1}$$

where,

M = Metabolic rate [W.m^{-2}];
W = External work [W.m^{-2}];
H = Dry heat losses [W.m^{-2}];
E_c = Evaporative heat exchange at the skin [W.m^{-2}];
C_{res} = Respiratory convective heat exchange [W.m^{-2}];

E_{res} = Respiratory evaporative heat exchange [W.m^{-2}].

The PMV model is accounted for by four environmental parameters including air temperature, mean radiant temperature, relative humidity, and air velocity, and two personal factors including metabolic rate (met) and clothing value (clo) to predict the average thermal sensation value of a large number of subjects by using the corresponding seven-point thermal sensation scale: +3: hot, +2: warm, +1: slightly warm, 0: neutral, -1: slightly cool, -2: cool, and -3: cold (ASHRAE Standard 55, 2004). Where PMV = 0, representing the thermal neutral sensation, has been determined to be the most appropriate thermal perception in a given space. The Predicted Mean Vote (PMV) for predicted thermal sensation value is calculated using the following relationship (Fanger, 1970) (Eq. 2):

$$PMV = (0.303 \cdot e^{-0.036 \cdot M} + 0.028) \cdot [(M - W) - H - E_c - C_{res} - E_{res}] \quad \text{Eq.2}$$

as,

$$PMV = (0.303 \cdot e^{-0.036 \cdot M} + 0.028) \cdot \{(M - W) - 3.05 \cdot 10^{-3}[5733 - 6.99(M - W) - p_a] - 0.42[(M - W) - 58.15] - 1.7 \cdot 10^{-5} \cdot M(5867 - p_a) - 0.0014 \cdot M(34 - t_a) - 3.96 \cdot 10^{-8} \cdot f_{cl}[(t_{cl} + 273)^4 - (t_r + 273)^4] - f_{cl}h_c(t_{cl} - t_a)\} \quad \text{Eq.3}$$

with,

$$t_{cl} = 35.7 - 0.028(M - W) - l_{cl}\{3.96 \cdot 10^{-8} \cdot f_{cl}[(t_{cl} + 273)^4 - (t_r + 273)^4] + f_{cl}h_c(t_{cl} - t_a)\} \quad \text{Eq.4}$$

$$h_c = \begin{cases} 2.38(t_{cl} - t_a)^{0.25} & for\ \left(2.38(t_{cl} - t_a)^{0.25} > 12.1\sqrt{v_{ar}}\right) \\ 12.1\sqrt{v_{ar}} & for\ \left(2.38(t_{cl} - t_a)^{0.25} < 12.1\sqrt{v_{ar}}\right) \end{cases} \quad \text{Eq.5}$$

$$f_{cl} = \begin{cases} 1.00 + 1.290 l_{cl} & for\ (l_{cl} < 0.078 m^2 °\mathrm{C} W^{-1}) \\ 1.05 + 0.645 l_{cl} & for (l_{cl} > 0.078 m^2 °\mathrm{C} W^{-1}) \end{cases} \quad \text{Eq.6}$$

$$v_{ar} = v_a + 0.005(M/A_{du} - 58.15) \quad \text{Eq.7}$$

where,

t_a = Air temperature [ºC];

t_r = Mean radiant temperature [ºC];

v_a = Air velocity [m.s^{-1}];

v_{ar} = Relative air velocity (relative to the human body) [m.s^{-1}];

p_a = Partial water vapor pressure [pa];

t_{cl} = Surface temperature of clothing [ºC];

f_{cl} = Ratio of clothing surface area;

h_c = Convective heat transfer coefficient [W.m^{-2}K^{-1}];

l_{cl} = Thermal resistance of clothing [m^{2}K.W^{-1}];

A_{du} = Dubious area [m^2];

The PMV index predicts the mean vote of a group of people's thermal sensation value in a given environment under steady state. While the Predicted Percentage Dissatisfied (PPD) index, assumed people who voted -3, -2, +2 and +3 on the PMV scale are regarded as thermal dissatisfaction, predicts the percentage of people who dissatisfied under this thermal conditions. The recommended PMV and PPD range for typical applications is the PMV between -0.5 and +0.5 indicating 10% of the occupant thermal dissatisfaction in a given environment (ASHRAE Standard 55, 2004; ISO 7730, 2005). The Predicted Percentage Dissatisfied (PPD) for predicted thermal comfort sensation is calculated using the following relationship (Fanger, 1970) (Eq. 8):

$$PPD = 100 - 95 \cdot \exp[-(0.03353 PMV^4 + 0.2179 PMV^2)] \quad \text{Eq.8}$$

2.1.2 ASHRAE Standard 55 and ISO 7730

Currently thermal comfort evaluation is judged according to two standards ASHREA Standard 55 (2004) published by American Society of Heating, Refrigerating, Air conditioning Engineers and ISO 7730 (2005) published by International Organization for Standardization. Both standards use the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD) (Fanger, 1970) methods which were geared toward thermally adapted individuals to establish thermal environmental conditions in steady state for human occupancy. The recommendation of thermal comfort zone in ASHRAE Standard 55 presents that 90% of occupants feel thermal satisfaction based at a relative humidity of 50%, and a mean relative velocity lower than 0.15 $m.s^{-1}$, when mean radiant temperature is equal to air temperature, a metabolic rate of 1.2 met, and clothing insulation was defined as 0.9 clo in winter and 0.5 clo in summer. Similarity, the same inputs were calculated in ISO 7730 but based on differences in thermal comfort data. However, ISO 7730 yields a similar operative temperature range. The recommendations made by ASHRAE Standard 55 and ISO 7730 are shown in Table 1 (Nakano, 2003).

Table 1 Thermal comfort conditions

	Season	Icl (clo)	Optimum operative temperature (°C)	Operative temperature range (°C)
ASHRAE Standard 55	Winter	0.9	22	20 – 23.5
	Summer	0.5	24.5	23 – 26
ISO 7730	Winter	0.9	22.2	20 – 24.3
	Summer	0.5	24.7	23– 26.4

Refer to 50% of relative humidity; less than 0.15 ($m.s^{-1}$) of mean relative velocity; mean radiant temperature equal to air temperature and 1.2 met of metabolic rate.

2.1.3 Theoretical consideration between the PPD model and the realistic dissatisfaction

Basically thermal sensation and thermal comfort are two different concepts. Kim et al. (2013) indicates that the PMV model used as an indicator is more for reflecting the subjective human thermal sensation, but not for reflecting subjective human thermal comfort sensation. The PPD based on the PMV scale may inappropriate for people's thermal comfort evaluation. Becker and Paciuk (2009) conducted documentation of occupant responses of thermal sensation, thermal comfort and thermal preference in both passive and actively conditioned (less than 25% were actually conditioned during the survey) residential buildings. The finding shows only less than fifty percent of respondents reported they were thermally comfortable when rating themselves slightly cool in the PMV scale in the winter sample. While in the summer sample, only 23% of respondents expressed being thermally comfortable when rating themselves as slightly warm in the PMV scale. It seems that conditions indicating PMV = -1 (slightly cool) in winter and PMV = +1 (slightly warm) in summer cannot be assumed to be satisfactory and seem to suggest participants prefer being warmer in winter and cooler in summer (Chun and Tamura, 1998; de Dear and Brager, 1998). This finding appears to present Fanger's assumption claims that the range of -1 to +1 in the PMV scale regarding thermal satisfaction is not appropriate. Moreover, the result shows the standard may more dependent on artificial controlled conditions without accounting for occupants' preferences in seasonal differences in naturally ventilated environments.

2.2 The adaptive approach

De Dear and Brager (2001) noted that "*current thermal comfort standards and the models underpinning them propose to be equally applicable across all types of building, ventilation, occupancy pattern and climate zone*". Moreover, these typical thermal comfort studies were conducted in a laboratory with European, college-age sedentary participants in western regions being the conventional parameters (Oleden and Parsons, 2002), while such as tropical regions including behavior of occupants and their expectations may be not applied appropriately (Humphreys and Nicol, 2000).

Nakano (2003) noted that the neutral temperature derived for Danish (Fanger, 1970), Singaporean (de Dear et al., 1991) and Japanese people (Tanabe and Kimura, 1994) yielded significant differences, suggesting that people from different climatic regions perceive different neutral temperatures. Oseland (1996) found that the PMV model correlated better with the sensation of occupants in air-conditioned buildings, as compared to the responses in naturally ventilated buildings. Moreover, de Dear and Brager (1998) concluded that the predicted neutral temperature is generally much closer to the actual neutral temperature responses in air-conditioned buildings, as compared to the responses in naturally ventilated buildings. However, authors suggested that occupants tolerate a wider range of air temperatures in naturally ventilated buildings, as compared to what occupants expressed in air-conditioned buildings. Beizaee et al. (2012) studied different usage of naturally ventilated buildings for home and office environments which could be a different view affecting occupants' thermal sensations. The adaptive approach relies on field studies with respect to the individual differences, building differences, climatic differences and behavior adaptation (Charles, 2003).

2.3 Standards with regard to non-steady states

To apply the thermal comfort evaluation in a steady state appropriately, both standards ASHREA Standard 55 (2004) and ISO 7730 (2005) listed limitations regarding non-steady states in the following situations.

Temperature cycles, described in both ASHREA Standard 55 (2004) and ISO 7730 (2005), refers to those situations where the operative temperature repeatedly rises and falls, and the period of these variations is not greater than 15 minutes. There are no restrictions on the rate of temperature change if the peak to peak variation in operative temperature exceeds 1.1 K or less. If the period of these variations is greater than 15 minutes, the variation is treated as a drift or ramp in operative temperature. Table 2 shows the allowable Cyclic Operative Temperature Variation.

Table 2 The allowable Cyclic Operative Temperature Variation (ASHRAE 55, 2004)

Allowable Peak-to-Peak Variation in Operative Temperature (K)	1.1

Temperature ramps or drifts, described in both ASHREA Standard 55 (2004) and ISO 7730 (2005), refers to those situations where the operative temperature drifts or ramps over a period greater than 15 minutes. For example, the operative temperature may not change more than 2.2K during a 1 hour period, and it also may not change more than 1.1K during 15 minutes within that 1 hour period. Table 3 shows the limits on temperature drifts and ramps.

Table 3 The limits on temperature drifts and ramps (ASHRAE 55, 2004)

Time Period (h)	0.25	0.5	1.0	2.0	4.0
Maximum Operative temperature Change Allowed (K)	1.1	1.7	2.2	2.8	3.3

Transients, mentioned in ISO 7730 (2005), refers to those situations when occupants move from one space to another within a sudden temperature step-change or enter a space where there isn’t enough time to stay for adaptation. The heat exchange between the human body and the environment would not reach the steady state in a short period and may immediately influence occupants’ thermal comfort response. The prediction may show too high a value for the first 30 minutes period if using typical standards (ThermCo, 2009).

2.4 The transitional states

As previously stated, a steady state rarely occurs in our daily life, thermal comfort in transitional states should be considered in order to provide a continuous thermal environmental condition in real experiences with several environmental step changes. Subjective thermal sensation and comfort evaluations of transitional states have been addressed in past research.

Berglung and Gonzalez (1978) conducted an experiment where subjects with different clothing insulations (0.5, 0.7 and 0.9 clo) experienced 7 rates of temperature change (0, ±0.5, ±1, ±1.5 K/h) based on 25°C. It was observed that the thermal responses to the temperature ramp of ±1 and ±1.5 K/h increased or decreased following the temperature changes. Moreover, the change of thermal response was steeper in the decreasing temperature ramp than the increasing temperature ramp, indicating that subjects were more sensitive to decreasing temperature.

Chun and Tamura (1998) conducted a field study investigating the difference in thermal responses between a space with stable thermal condition (such as department store) and a semi-opened space (transitional space) such as underground shopping mall. The study indicated the acceptable range of temperature is narrow when people were exposed to a thermally stable condition as compared to a transitional space. Emphasizing the importance of temperature change in transitional states affecting the perception of thermal comfort. Chun and Tamura (2005) also conducted a laboratory-based study involving subjects walking through controlled chambers in sequence. They suggested that thermal comfort perception at a certain point in time is influenced by antecedent thermal conditions.

Gagge et al. (1967) conducted a series of subjective experiments where subjects were exposed to thermally neutral conditions (28-30°C) for an hour, then moved to much warmer (48°C) or much colder (12°C) environments for two hours exposure and vice versa. Subjects expressed cold or warm as well as uncomfortable sensation immediately after entering the cold or warm environments from the neutral. On returning to the neutral environment, comfortable expression showed immediately, but their thermal sensation returned slowly after the move from the cold to the neutral environment, whereas the subjects responded that they were cold initially then returned even more slowly to neutrality after the move from the hot to neutral environment. Rohles et al. (1977) have conducted a similar experiment to investigate the super market experience. The thermal sensation and comfort responses reached a steady state very quickly and their thermal comfort was not affected by previous uncomfortable experience when moving through a transition from uncomfortable to comfortable environments.

Arens et al. (2006)'s results are consistent with de Dear et al. (1993)'s finding which reported that the thermal sensation responses immediately after a transition involving temperature increase have been reported to be close to the responses after adaptation, whereas the thermal sensation responses immediately after a temperature decrease dropped initially to return to a stable level after adaptation. Chen et al. (2011) showed similar results and observed that the initial drop of thermal sensation responses mostly follow a larger cold step-change and suggested the temperature difference should be limited to 4 K in order to maintain adequate thermoregulatory function.

Nakano (2003) conducted an experiment with a buffer zone between two environments with different temperatures, which suggested that transitions involving large temperature intervals towards thermal neutrality result in a correspondingly large improvement of thermal comfort feedback.

Hwang et al. (2008) conducted a field study which demonstrated differences between the immediate thermal responses of visitors versus resident staff experiencing a temperature step from an outdoor to an indoor waiting zone in a public space. The results indicated that the guests could tolerate a wider range of environmental conditions and prefer a lower temperature when they moved from a hot to a cold environment than those staff who were constantly in a steady environment.

Parkinson et al. (2012) indicated that sudden changes in ambient temperature can induce thermal pleasure, giving a positive alliesthesial effect. However, the same environmental step change invoked a displeasure response when the core temperature was stable.

3 Methodology

For general subjective research about human thermal sensation and comfort evaluations, experiments and questionnaires were conducted to investigate the influence of various factors on how a person feels about a specific environment. This chapter, which describes the method of research, includes two main sections. The first section details the methodology of the laboratory experiments. The second section presents a similar experimental design, but in a field study in the Museum of Art History (Kunsthistorisches Museum) in Vienna, Austria.

3.1 Laboratory study

Our laboratory study included a number of experiment in the spring and winter periods. The spring experiments were conducted in the beginning of May 2012 over a period of 5 days and the winter experiments were conducted in the middle of December 2012 over a period of 2 days, during daytime from 9 am to 6 pm in a laboratory setting (Department of Building Physics and Building Ecology, Vienna University of Technology, Vienna, Austria). The idea of thermal sensation and comfort under transitional situation is shown in Figure 1.

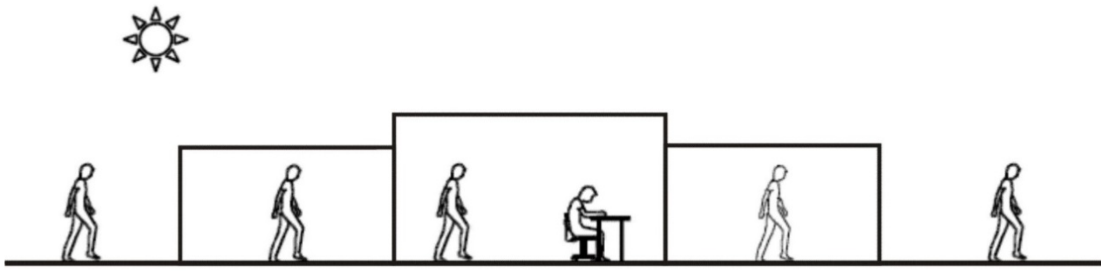

Figure 1 Image of the experimental procedure for thermal sensation and comfort assessment

3.1.1 Research design

A subjective experiment was designed to simulate an occupant's experiences in a spatial transition with various environmental step changes. Figure 2 schematically illustrates this setting and the experiment's spatial arrangement. Here, E denotes the external environment (open courtyard) and M is a general (unconditioned) 8 by 10 m laboratory space (height = 5 m). A and B are two equally sized (3 by 4 m, height = 2.5 m) mock-up office rooms. M was mechanically ventilated throughout the two phases of the experiment (conducted in spring and winter). However, it was not thermally controlled (cooled) during the spring session. A basic level of heating was provided during the winter session. A and B were either heated or cooled according to the experimental setup and seasonal conditions.

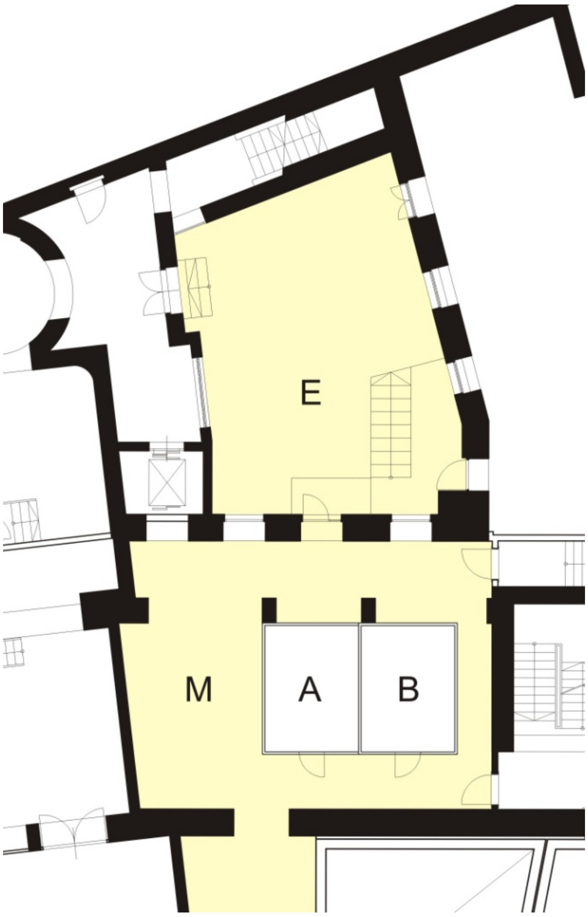

Figure 2 Schematic illustration of the test spaces

3.1.1.1 Environmental installation

In the winter semester of 2012, together with the students who participated in the course of Human Ecology at Vienna University of Technology, we prepared the test room in our laboratory.

In order to build various thermal transitions by going through one room to the other with temperature differences, two mock-up office rooms included in the test room had to be built one as a heated room and the other a cooled room (see Figure 3). We installed a heater in room A and an air conditioning in room B in order to provide a heated and a cooled environment. And test room M was kept to a general mechanically ventilated environment with basic level of heating during the winter season, but was not thermally controlled during the spring season.

Figure 3-1 Heated room

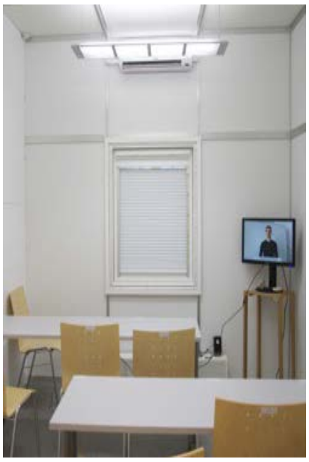

Figure 3-2 Cooled room

Figure 3 Heated and cooled spaces

In order to maintain a certain temperature of each space, we improved the wall insulation of the two mock-up office rooms by installing 5 cm thick Expanded polystyrene (ESP) panel, covering all internal and external walls of each chamber to increase thickness from a nominal 2 cm to 12 cm (see Figure 4). Moreover, before covering with ESP panels, we sealed all gaps of the mocked office with plastic tape (see Figure 4-2) and constructed a wooden frame for all internal and external walls of each chamber to place the ESP panels easily (see Figure 4-3).

Figure 4-1

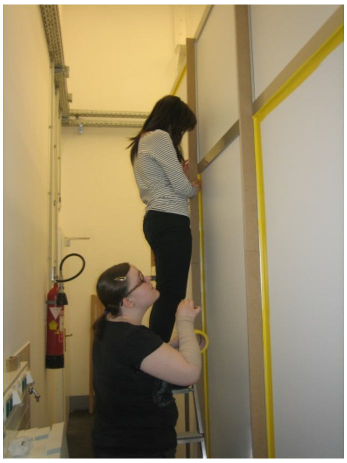

Figure 4-2

Figure 4-3

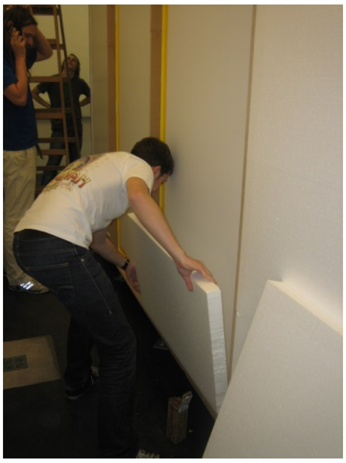

Figure 4-4

Figure 4-5

Figure 4-6

Figure 4 ESP panels installation

3.1.1.2 Monitoring equipments

The facility is equipped with a monitoring system facilitating the continuous collection of data regarding thermal conditions in the test spaces. Specifically, indoor air temperature, relative humidity, CO_2 concentration, and illuminance levels were monitored during all experiments.

HOBO® data loggers, monitoring sensors and a weather station were used to collect data in our experiments. The Davis vantage pro2 weather station (See Figure 5-1) monitored and collected the outdoor data includes air temperature, relative humidity and wind speed. The HOBO® U12-012 loggers (See Figure 5-3) were used indoors to collect air temperature, relative humidity and illuminance levels. While the indoor CO_2 concentration were monitored via Telaire 7001 CO_2 sensors (See Figure 5-4).

Figure 5-1 Davis vantage pro2 weather station

Figure 5-2 Davis vantage pro2 monitor

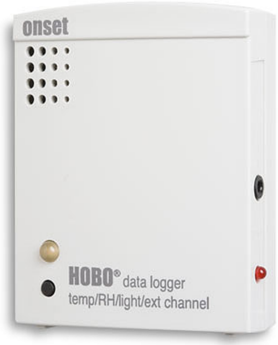

Figure 5-3 HOBO® U12-012 loggers

Figure 5-4 Telaire 7001 CO_2 sensors

Figure 5 Overview of measuring devices

The Davis vantage pro2 weather station was located in the courtyard at a height of about 2 meters and collected outdoor data every 5 minutes. The HOBO® data loggers were placed at a height of 1.6 meter near every indoor entrances and also placed at a height of 1 meter in the two test cells for documenting the data every minute when people in sedentary situation. Figure 6 schematically illustrates the location for all monitoring sensors.

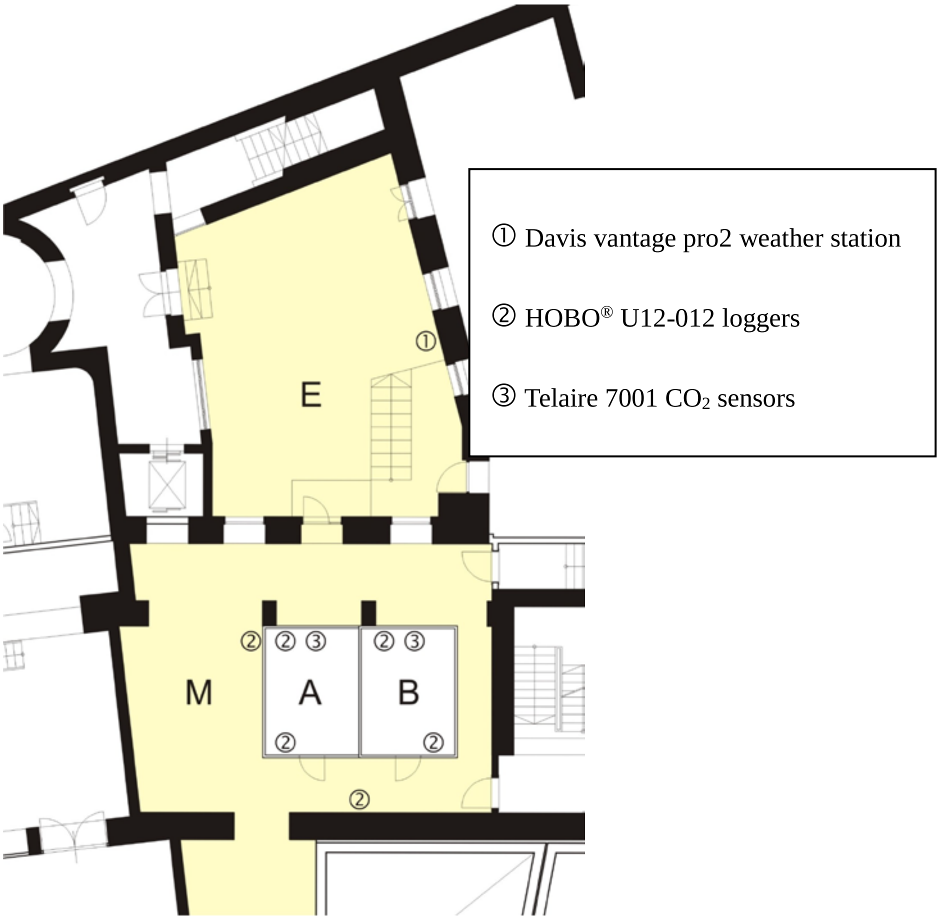

Figure 6 Schematic illustration of location for monitoring systems

3.1.2 Subjects

In our experiments, we were able to conduct the experiments with participants (students at the Vienna University of Technology) in spring and winter 2012. The general relative information of subjects describes in Table 4 for the spring and winter periods respectively. The number of participants in the spring session was 313 (56% female, 44% male) and in the winter session was 84 (43% female, 57 % male). The mean age of participants in the spring session was 22 ± 3 and that of participants in the winter session was 26 ± 3. The thermal resistance of the participants' clothing (expressed in units of clo), which remained unchanged throughout the experiment, was documented base on visual inspection (ASHRAE Handbook, 2005) in steady state in an unconditioned space, revealing 0.6 ± 0.15 clo during the spring session and 1.2 ± 0.18 clo during the winter session. Ideally, experiments should be conducted at different times during the year, such that different outdoor conditions and corresponding clothing variations are captured.

Table 4 Anthripometric data of subjects for the spring and winter periods respectively

	Spring			**Winter**		
	All	Female	Male	All	Female	Male
Number	313	175	138	84	36	48
Age	21.6 ± 3.1	21.0 ± 3.3	22.4 ± 2.7	25.8 ± 3.0	25.5 ± 2.8	26.0 ± 3.1
Height (cm)	173.8 ± 9.6	167.7 ± 6.4	181.5 ± 7.0	174.7 ±10.4	165.3 ± 6.9	181.8 ± 6.1
Weight (kg)	66.0 ± 12.1	58.9 ± 8.0	75.0 ± 10.3	68.2 ± 14.5	54.7 ± 7.3	78.2 ± 9.5

3.1.3 Questionnaire

The questionnaire consisted of two main parts. The first part documented the participants' basic information including gender, age, job occupation, nationality. The most important value of each participant's clothing insulation was documented before the experiment. In the second part, participants were requested to express their thermal sensation vote (TSV) using a 7 points scale (-3: cold, -2: cool, -1: slightly cool, 0: neutral, 1: slightly warm, 2: warm, 3: hot) (ASHRAE 55, 2004 and ISO 7730, 2005) and their thermal comfort vote (TCV) using a 6 points scale (-3: very uncomfortable, -2: uncomfortable, -1: just uncomfortable, 1: just comfortable, 2: comfortable, 3: very comfortable) (Zhang, 2003) via a questionnaire (see Figure 7) immediately after a spatial transition and after a short period of adaptation. Note that thermal preference vote (TPV) of participants were collected as well in the winter session by using 3 points scale (-1: prefer cooler, 0: no change, 1: prefer warmer) (see Appendix A).

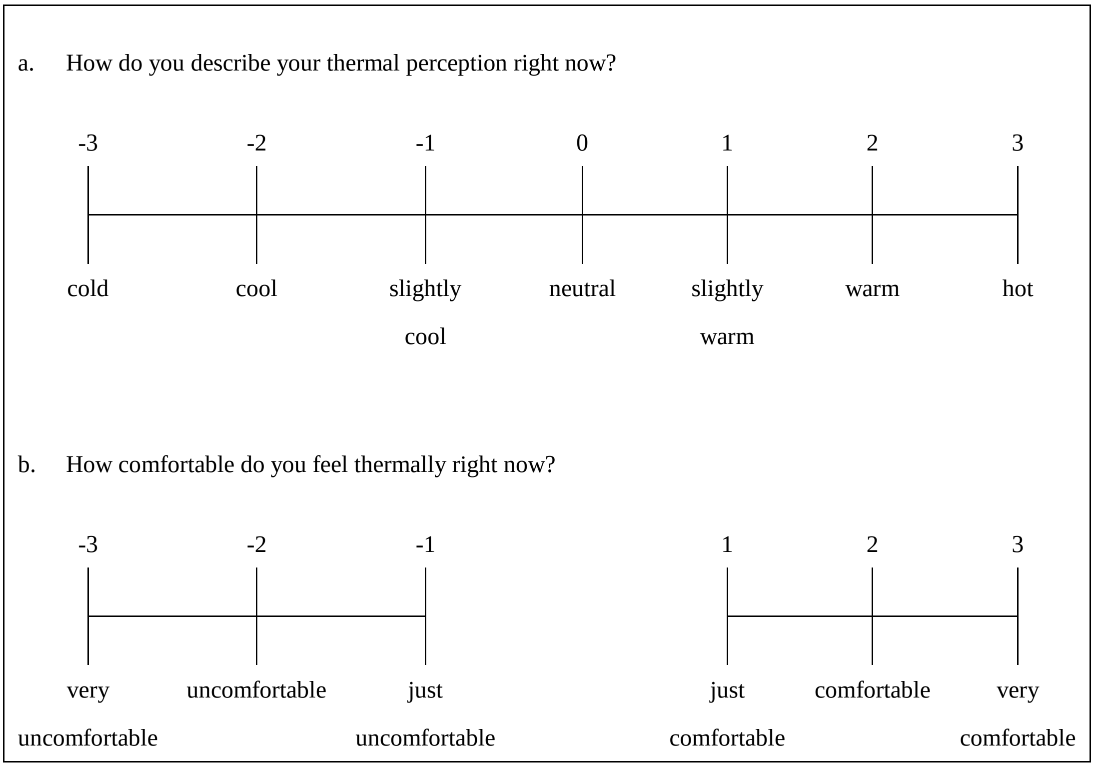

Figure 7 Voting Scale

3.1.4 Experimental procedure

Each round of the experiment consisted of 2 groups with different exposures of temperature step-change (the heated or cooled room). Participants were divided into multiple groups, each consisting of 6 individuals. The composition of the groups was basically random. However, to the greatest possible extent, an equal number of male and female participants were assigned to each group. The thermal resistance of the participants' clothing, which remained unchanged throughout the experiment, was documented at the beginning of the experiment.

Prior to each transition (walking from one room to another), participants were adapted to thermal conditions in a sedentary position. In literature (Arens et al., 2006; Nagano et al., 2005; Zhang, 2003), adaption phases of 10 to 20 minutes have been found appropriate. In our experiments, participants spent at least 15 minutes in a sedentary state. Immediately after each transition, the participants' thermal sensation and comfort vote were assessed via a questionnaire. After an adaptation phase of approximately 15 minutes (also in sedentary position), votes were collected again. The experimental procedure is illustrated schematically in Figure 8 and all groups went through a sequence of spatial transitions as summarized in Table 5. Figure 9 presents the processes and activities of each step.

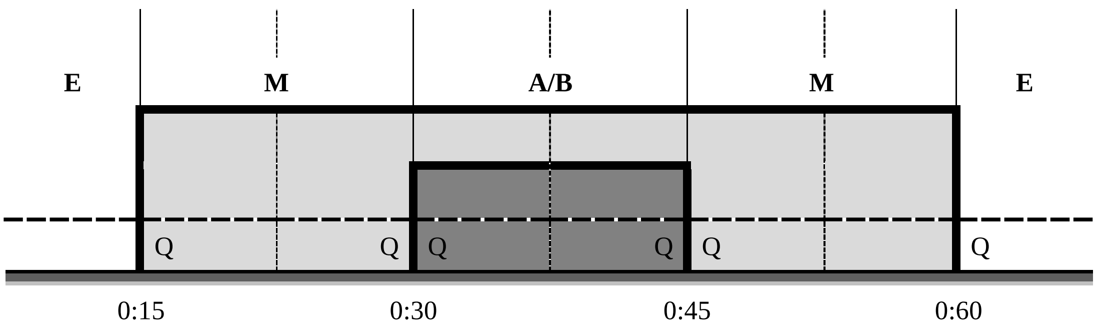

Figure 8 Schematic illustration of the experimental procedure (Q: Questionnaire)

Table 5 Overview of the spatial transitions (see Figure 2 for room symbols) and the respective number of participants

	Spatial transition	Number of participants	
		Spring	Winter
1	M_A	154	41
2	M_B	152	38
3	A_M	155	42
4	B_M	158	42
5	E_M	313	84
6	M_E	311	84

Figure 9-1 the courtyard (E)

Figure 9-2 Spatial transition 5 (E_M)

Figure 9-3 The laboratory (M)

Figure 9-4 The heated and cooled room (A)(B)

Figure 9-5 Entrance of the heated room (A_M)

Figure 9-6 Entrance of the cooled room (B_M)

Figure 9 Image of the experimental procedure

3.1.5 Statistical analysis

In the treatment of the results, the votes of the six participants constituting each group was averaged and processed for further analyses and interpretation. The main reason for this approach was the fact that all members of each group were exposed to exactly the same thermal conditions before and after the transition. Moreover, this grouping facilitated a more clear representation and visualization of the results without changing the main truth of the statistical analyses and the associated results.

To compare participants' expressed thermal sensation votes (TSV) with steady-state thermal comfort model predictions, we calculated the PMV values (ASHRAE Standard 55, 2004; ISO 7730, 2005) using measured indoor environmental variables (i.e., air temperature, relative humidity) and known personal factors (clothing, activity) in all instances. To maintain consistency in data analysis, the corresponding calculated PMV values used in statistical analysis were also averaged for each group of six participants who experienced identical indoor environmental conditions in the course of thermal transition. Note that the indoor air velocity and mean radiant temperature could not be measured continuously in the test cells. Conducted spot measurements, however, suggest that indoor air velocity in the test cells did not exceed a value of 0.15 $m.s^{-1}$. Moreover, indoor surface temperatures of the test cells did not deviate from the indoor air temperature in a noteworthy manner. Hence, for the PMV calculation, mean radiant temperature was assumed to be equal to the measured room air temperature and the mean indoor air velocity was set to 0.15 $m.s^{-1}$. As PMV was consistently calculated for the participants in sedentary activity, a metabolic rate of 1.2 MET (general office-type activity) was used for PMV calculations.

Given the difference in the number of participants in spring and winter, statistical analyses were not only conducted for the entire data set, but also separately for spring and winter.

3.2 Field study

Field experiments were conducted at the beginning of June 2012 over a period of 2 days from 10 am to 5 pm in the Museum of Art History (Kunsthistorisches Museum) in Vienna, Austria. The outdoor temperature range in this period was between 17.2 and 23.0 °C, and the indoor temperature range was between 20.0 and 25.7 °C.

Figure 10 schematically illustrates floor plans and the experiment's spatial arrangement. "E" denotes the external environment and the numbered spaces are conditioned indoor environments. Five spatial transitions are summarized in Table 6. During the experiments, we measured indoor air temperature and relative humidity continuously around the facility.

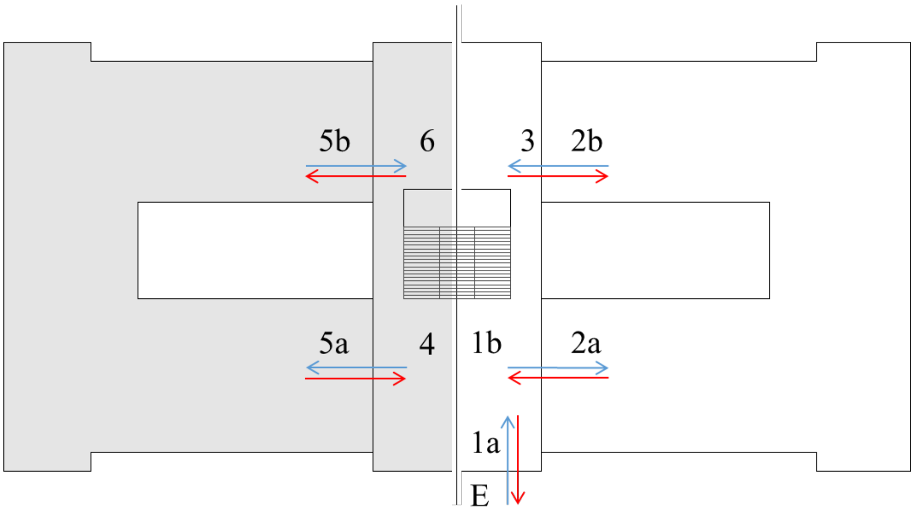

Figure 10 Schematic illustration of the test spaces (left part: first floor; right part: ground floor)

Table 6 Circulation plan for route 1 and route 2

Spatial transition	Route 1	Route 2
1	E_1a	6_5b
2	1b_2a	5a_4
3	2b_3	3_2b
4	4_5a	2a_1b
5	5b_6	1b_E

The number of participants (students at the Vienna University of Technology) in the experiments was 77 (63% female, 34% male) and the mean age of participants was 22±3. The participants were divided into 8 groups, each consisted of up to 10 individuals. The composition of the groups was basically random.

Participants moved in groups along two predefined routes, each route involved five spatial transitions (see Figure 11) as summarized in Table 6. The thermal resistance of the participants' clothing was about 0.6 clo. Participants spent at least 10 minutes in each space engaged in low activity (standing, walking a few steps) prior to each transition (walking from one room to another). Immediately after each transition, the participants expressed their thermal sensation vote (TSV) using a 7 points scale (-3: cold, -2: cool, -1: slightly cool, 0: neutral, 1: slightly warm, 2: warm, 3: hot) (ASHRAE Standard 55, 2004) and their thermal comfort vote (TCV) using a 6 points scale (-3: very uncomfortable, -2: uncomfortable, -1: just uncomfortable, 1: just comfortable, 2: comfortable, 3: very comfortable) (Zhang, 2003) via a questionnaire. In the treatment of the results, the votes of ten participants constituting each group was averaged and processed for further analyses and interpretation. Same concern as the previous laboratory studies, the main reason for this approach was the fact that all members of each group experienced similar thermal conditions before and after the transition. Moreover, this grouping facilitated a more clear representation and visualization of the results without changing the main truth of the statistical analyses and the associated results.

To compare participants' expressed thermal sensation vote (TSV) with steady-state thermal comfort model predictions, we calculated for all instances the PMV values using measured indoor environmental variables (i.e., air temperature, relative humidity) and known personal factors (clothing, activity). Mean radiant temperature was assumed to be equal to the measured room air temperature and the mean indoor air velocity was set to be 0.15 $m.s^{-1}$. As to participants’ activity level, a value of 1.7 met (ASHRAE Handbook, 2005) was used for PMV calculations.

Figure 11-1 Spatial transition 1

Figure 11-2 Spatial transition 2

Figure 11-3 Spatial transition 3

Figure 11-4 Spatial transition 4

Figure 11-5 Spatial transition 5

Figure 11-6 Spatial transition 5

Figure 11 Image of spatial transitions (refer to Table 6 spatial transition)

4 Results

As in the previous chapter, this chapter includes two main sections. The first section presents the results of collected data from the laboratory study, then based on this data, describes the development of a new measurement for predicting people's thermal comfort under transitional conditions. The second section presents the results of this thermal prediction when applied to a field study in the Museum of Art History (Kunsthistorisches Museum) in Vienna, Austria.

4.1 Results of laboratory study

The results of participants' thermal sensation and comfort evaluation and the related environmental measurements during our experiments were collected before transition, immediately after the spatial transition and after a short period of adaptation. The corresponding PMV values were also calculated using applicable clo value for clothing insulation and a general value of 1.2 met for activity level.

4.1.1 Data collections

The data collection includes three main aspects, environmental parameters, personal data and the participants' thermal responses.

4.1.1.1 Environmental parameters

The experiment was conducted in the spring and winter seasons. Table 7 shows the statistical summary of the environmental data in spring and winter respectively. The mean value of outdoor air temperature (E) in the spring period was 19 ºC and 3 ºC in the winter period. While the mean value of unconditioned indoor air temperature (M) in the spring period was about 25 ºC and 22 ºC in the winter period. In both spring and winter sessions, the air temperatures of the heated cell (A) and the cooled cell (B) were kept at 27 ºC and 17 ºC respectively. The mean value of relative humidity in the spring season, for both outdoor and indoor, was around 40%. While the mean value of outdoor relative humidity in winter was relatively higher (72%) than in the spring season. Moreover, as expected, the mean value of relative humidity in winter was a bit lower (30%) in space (M) and (A) due to the heated conditions. Note that the statistical summary of relative CO_2 concentration and illuminance level shows in Appendix B.

Table 7 Statistical summary of environmental variables for the spring and winter periods respectively

		Spring season				Winter season			
		Av.	S.D.	Max.	Min.	Av.	S.D.	Max.	Min.
Ta (ºC)	E	19.04	5.37	29.80	11.56	3.49	1.51	4.94	0.50
	M	24.89	1.05	27.16	22.27	21.64	0.43	22.61	20.87
	A	26.82	1.58	29.77	22.54	27.40	1.16	28.64	24.53
	B	17.88	1.00	20.27	15.63	17.23	0.69	18.32	15.99
RH (%)	E	46.37	16.23	78.60	23.00	71.95	1.91	76.00	69.00
	M	37.11	5.57	46.80	26.37	29.96	0.82	31.40	28.50
	A	39.10	6.54	55.28	24.05	27.94	3.29	34.34	23.29
	B	40.74	4.19	49.77	31.64	39.37	3.43	43.92	31.18

Av. = average over entire group; S.D. = standard deviation; Max., Min. = maximal and minimal recorded values; Ta = air temperature near seated person; RH = relative humidity near seated person

4.1.1.2 Personal data

For the spring and winter experiments, we observed a wide range of clothing insulation (clo) between 0.09 and 2.37 clo in the indoor environment. Detailed information of clothing value for spring and winter is summarized separately in Table 8 which measured adapted sedentary participants under a steady environment which almost approaching 80 percent of occupants (ASHRAE Standard 55, 2004; ISO 7730, 2005) were thermally satisfied with (see Appendix C). Figure 12 displays the linear regression function between clothing value and indoor air temperature with a coefficient of determination R^2 = 0.50, indicating that increasing indoor air temperature results in decreasing clothing value. This result is generally consistent with but constantly higher than the function between clothing level and operative temperature represented in ASHRAE Standard 55 (2004) and Prabath (2013) regarding the conditions which at least 80 percent of occupants found thermally acceptable.

Figure 13 presents the same information as Figure 12, but between clothing value and outdoor air temperature. The coefficient of determination of the linear regression is a bit higher than the one in Figure 12, somehow reflecting that the outdoor air temperature might be a greater factor influencing clothing value, particular in the winter session (Cao et al., 2007; Centnerova and Hensen, 2001).

Table 8 Statistical summary of clothing insulation (clo) for the spring and winter periods respectively

		Spring season			Winter season		
		All	Female	Male	All	Female	Male
Clothing insulation (clo)	Av.	0.58	0.62	0.52	1.25	1.35	1.17
	S.D.	0.24	0.26	0.21	0.32	0.26	0.33
	Max.	1.52	1.52	1.12	2.37	1.75	2.37
	Min.	0.09	0.09	0.16	0.62	0.85	0.62

Av. = average over entire group; S.D. = standard deviation; Max., Min. = maximal and minimal recorded values

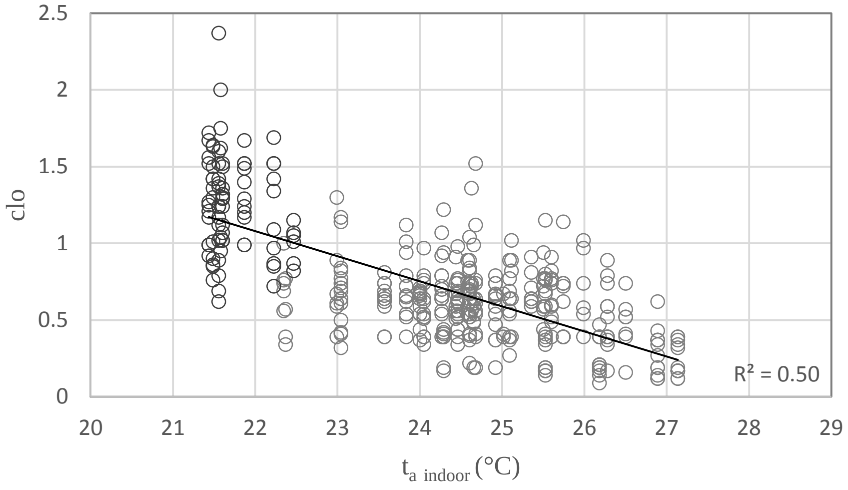

Figure 12 Distribution of clothing insulation (clo) of the thermally adapted participants versus indoor air temperature (ºC)

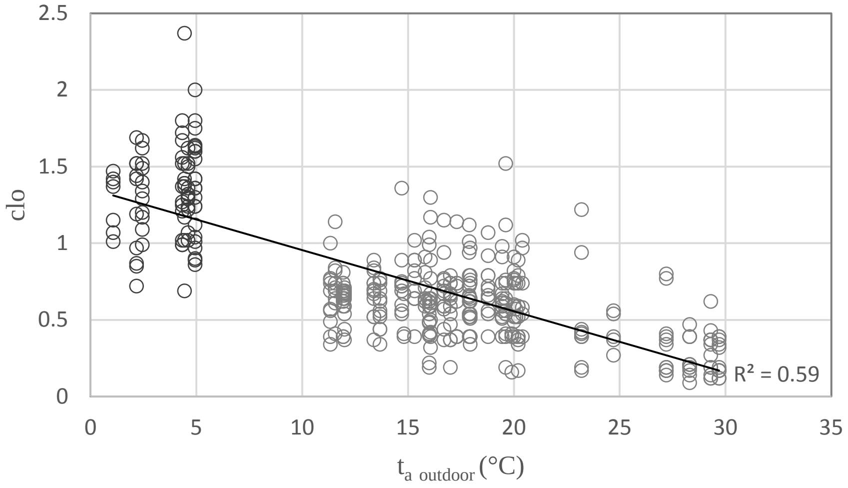

Figure 13 Distribution of clothing insulation (clo) of the thermally adapted participants versus outdoor air temperature (ºC)

The clothing value was also documented for male and female respectively. Figure 14 and Figure 15 show that the clothing values of males were constantly lower than the values of females, reflecting that woman prefer a warmer environment than man (Ugursal, 2010; Wang, 2006).

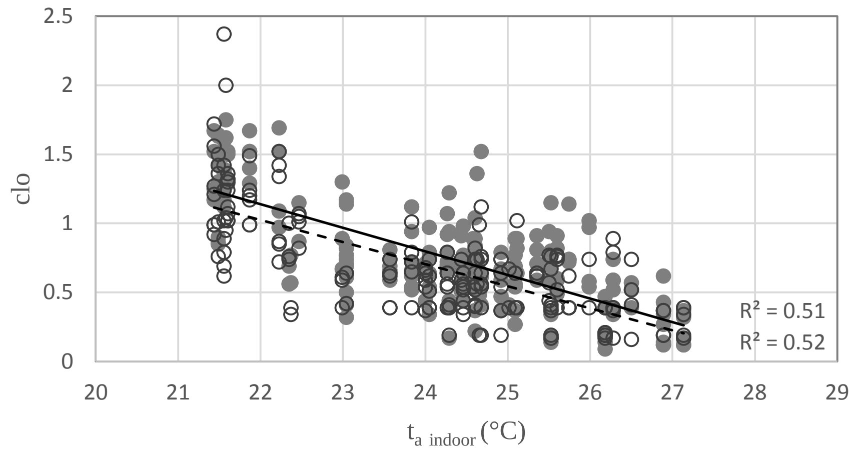

Figure 14 Distribution of clothing insulation (clo) of the thermally adapted participants versus indoor air temperature for male (white dots, dashed regression line) and female (black dots, continuous regression line) respectively

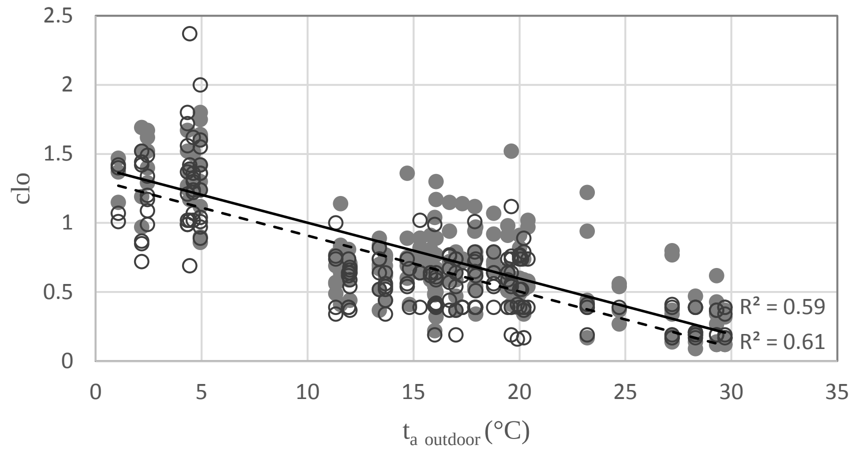

Figure 15 Distribution of clothing insulation (clo) of the thermally adapted participants versus outdoor air temperature for male (white dots, dashed regression line) and female (black dots, continuous regression line) respectively

4.1.1.3 Thermal sensation and comfort responses

The thermal sensation and thermal comfort votes of participants were expected to be different due to environmental perception and different time phases following a transition with environmental changes. Therefore subjective data was collected before transition, immediately after the spatial transition in transitional state, and after a short period adaptation in a steady state. Table 9 and Table 10 summarize average votes and distributions of the thermally adapted participants' thermal sensation vote (TSV) and thermal comfort vote (TCV) in a steady state for spring and winter periods respectively. Table 11 and Table 12 summarize the similar information for spring and winter periods respectively but reported their thermal responses immediately after a spatial transition. In this data, the comparisons of participants' thermal sensation and comfort assessments between the responses expressed immediately after a spatial transition and their responses after adaptation in steady state for each transition are presented in Appendix C. Basically, except the transition outdoor to indoor E-M in the spring session, a larger percentage of thermal comfort experience was found to expressed immediately after a spatial transition in transitional state as compared to the one of thermally adapted participants in steady state (Pitts, 2013).

Table 9 Thermal responses of thermally adapted participants in a steady condition, spring sample (n = 313)

		Av.	-3	-2	-1	0	1	2	3
TSV			(% of respondents in category)						
	M	0.94	0.00%	0.00%	2.24%	23.40%	53.53%	20.19%	0.64%
	A	1.39	0.00%	1.30%	3.90%	15.58%	22.08%	48.05%	9.09%
	B	-2.36	55.05%	31.01%	10.13%	2.53%	1.27%	0.00%	0.00%
TCV		Av.	-3	-2	-1		1	2	3
			(% of respondents in category)						
	M	1.00	0.64%	3.53%	15.71%		37.82%	39.74%	2.56%
	A	-0.47	4.55%	18.18%	44.81%		18.83%	11.69%	1.95%
	B	-1.42	23.57%	38.85%	19.75%		10.19%	7.01%	0.64%

n = number of participants; TSV = thermal sensation vote; TCV = thermal comfort vote; Av. = average grade of thermal response in steady state.

Table 10 Thermal responses of thermally adapted participants in a steady condition, winter sample (n = 84)

		Av.	-3	-2	-1	0	1	2	3
TSV			(% of respondents in category)						
	M	0.13	3.66%	4.88%	15.85%	37.80%	25.61%	12.20%	0.00%
	A	2.17	2.38%	0.00%	0.00%	2.38%	11.90%	38.10%	45.24%
	B	-1.97	36.11%	33.33%	25.00%	2.78%	2.78%	0.00%	0.00%
TCV		Av.	-3	-2	-1		1	2	3
			(% of respondents in category)						
	M	0.50	1.22%	8.54%	21.95%		45.12%	21.95%	1.22%
	A	-1.12	21.43%	38.10%	16.67%		7.14%	11.90%	4.76%
	B	-1.53	11.11%	47.22%	33.33%		8.33%	0.00%	0.00%

n = number of participants; TSV = thermal sensation vote; TCV = thermal comfort vote; Av. = average grade of thermal response in steady state.

Table 11 Thermal responses reported immediately after a transition, spring sample (n = 313)

TSV		Av.	-3	-2	-1	0	1	2	3
			(% of respondents in category)						
	E-M	1.00	0.00%	0.00%	2.24%	19.81%	54.31%	23.32%	0.32%
	M-E	-0.77	4.82%	23.15%	35.05%	25.40%	5.14%	5.14%	1.29%
	M-A	0.79	0.00%	0.00%	7.79%	36.36%	27.27%	26.62%	1.95%
	A-M	-0.82	0.65%	14.19%	55.48%	27.10%	1.29%	1.29%	0.00%
	M-B	-2.16	31.58%	54.61%	13.16%	0.00%	0.66%	0.00%	0.00%
	B-M	1.09	0.00%	1.90%	1.27%	23.42%	33.54%	39.24%	0.63%
TCV		Av.	-3	-2	-1		1	2	3
			(% of respondents in category)						
	E-M	0.96	0.32%	3.83%	17.89%		35.46%	40.89%	1.60%
	M-E	1.07	1.29%	5.14%	20.26%		17.68%	43.41%	12.22%
	M-A	0.87	0.65%	5.19%	17.53%		39.61%	33.77%	3.25%
	A-M	1.68	1.29%	0.00%	7.10%		18.06%	60.00%	13.55%
	M-B	-0.55	9.87%	25.66%	27.63%		21.05%	14.47%	1.32%
	B-M	1.56	0.00%	3.16%	10.13%		16.46%	54.43%	15.82%

n = number of participants; TSV = thermal sensation vote; TCV = thermal comfort vote; Av. = average grade of thermal response immediately after a spatial transition.

Table 12 Thermal responses reported immediately after a transition, winter sample (n = 84)

TSV		Av.	-3	-2	-1	0	1	2	3
			(% of respondents in category)						
	E-M	0.70	1.19%	3.57%	10.71%	17.86%	41.67%	25.00%	0.00%
	M-E	-2.06	38.10%	33.33%	25.00%	3.57%	0.00%	0.00%	0.00%
	M-A	2.22	0.00%	0.00%	2.44%	0.00%	7.32%	53.66%	36.59%
	A-M	-1.33	9.52%	35.71%	38.10%	11.90%	4.76%	0.00%	0.00%
	M-B	-1.74	21.05%	36.84%	36.84%	5.26%	0.00%	0.00%	0.00%
	B-M	0.17	2.38%	7.14%	19.05%	26.19%	33.33%	11.90%	0.00%
TCV		Av.	-3	-2	-1		1	2	3
			(% of respondents in category)						
	E-M	0.96	0.00%	4.76%	15.48%		45.24%	27.38%	7.14%
	M-E	-0.93	11.90%	25.00%	39.29%		16.67%	5.95%	1.19%
	M-A	-0.56	4.88%	31.71%	29.27%		19.51%	12.20%	2.44%
	A-M	0.29	7.14%	14.29%	16.67%		35.71%	19.05%	7.14%
	M-B	-0.82	5.26%	34.21%	31.58%		23.68%	5.26%	0.00%
	B-M	0.21	2.38%	9.52%	28.57%		45.24%	11.90%	2.38%

n = number of participants; TSV = thermal sensation vote; TCV = thermal comfort vote; Av. = average grade of thermal response immediately after a spatial transition.

4.1.2 Data analysis

Due to statistical analysis of relative humidity revealing minor differences in participants' TSV and TCV responses, we focused on the effects of temperature step changes during transitions. All data of TSV of participants who experienced a spatial transition were compared to the corresponding values of PMV, considering the effects of thermally adapted and non-adapted participants, seasonal differences, temperature step changes and thermal experiences following a transition away from neutrality or toward neutrality.

4.1.2.1 Steady and transitional states

Figure 16 compares, for both spring and winter periods, the TSV of all thermally adapted participants versus the corresponding calculated values of PMV. The expressed TSV were generally consistent with the calculated values of PMV model (ASHRAE 55, 2004; ISO 7730, 2005) with a coefficient of determination of 0.74 (r = 0.86, p < 0.01). As mentioned before, each dot represents the mean value of the votes of a group of six participants who experienced exactly the same environment.

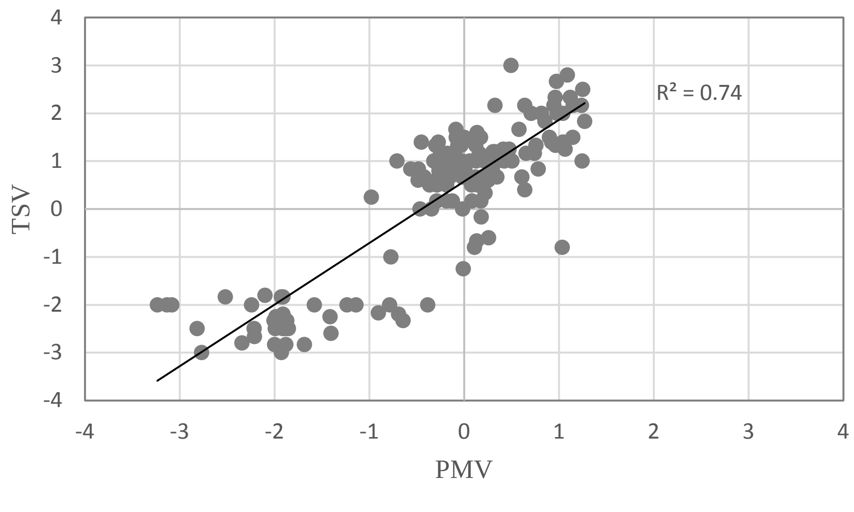

Figure 16 Thermal sensation vote (TSV) of thermally adapted participants versus the calculated values of PMV (all data)

Figure 17 entails the same information as Figure 16, but in this case the relationship between participants' TSV expressed immediately after transition (before adaptation) and the corresponding calculated values of PMV is included as well with a coefficient of determination of 0.57 (r = 0.75, p < 0.01). Calculated PMV values correlate better with thermally adapted participants' TSV as compared to non-adapted participants' votes.

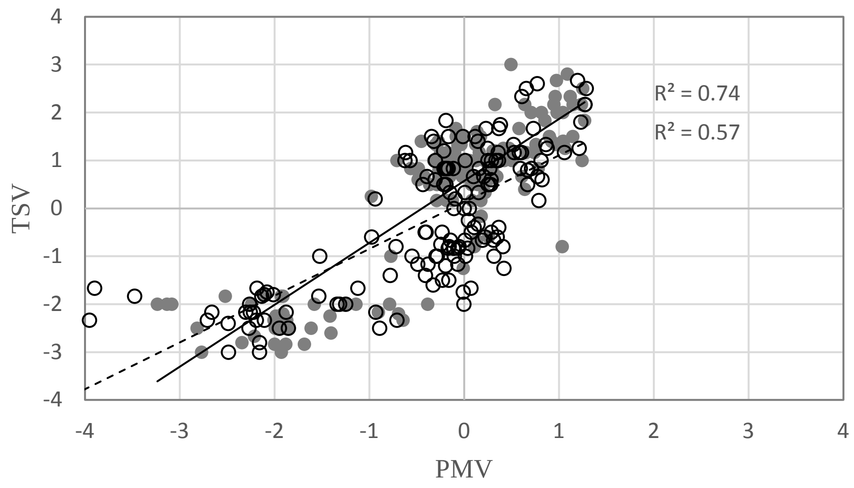

Figure 17 Participants' thermal sensation vote (TSV) reported immediately after transition (white dots) and after adaptation (black dots) versus the calculated values of PMV (all data)

4.1.2.2 Seasonal differences

Considering effects of seasonal differences, Figure 18 illustrates the same information as Figure 16 between TSV expression of all thermally adapted participants and the calculated values of PMV, but the regression line of the data from the spring (white dots, dashed regression line) (r = 0.89, p < 0.01) and from the winter (black dots, continuous regression line) (r = 0.88, p < 0.01) periods are distinguished but both are well correlated. The steeper slope of the regression line for winter data was observed, presenting a more pronounced thermal response of the adapted participants to the prevailing temperatures (Oseland, 1994) and – as compared to PMV-based predictions – a narrower tolerance range in view of thermally acceptable indoor conditions.

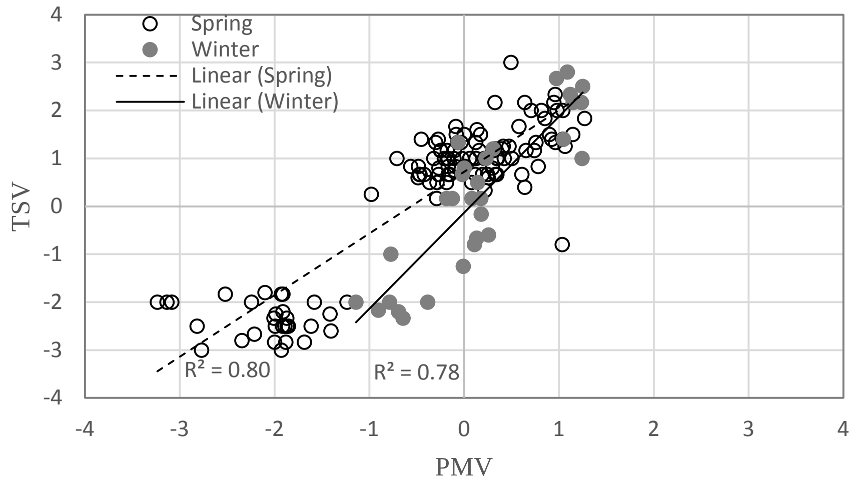

Figure 18 Thermal sensation vote (TSV) of thermally adapted participants versus the calculated values of PMV depicted separately for the spring (white dots, dashed regression line) and winter (black dots, continuous regression line) periods

Figure 19 illustrates the participants' TSV expressed immediately after transition versus the calculated values of PMV depicted separately for the spring (white dots, dashed regression line) (r = 0.76, p < 0.01) and winter (black dots, continuous regression line) (r = 0.85, p < 0.01) periods. The slope of the regression line in the winter period was also observed to be much steeper than the regression in the spring period. As compared to the responses of all thermally adapted participants in Figure 18, it can be observed in transitional states that participants' TSV revealed a larger acceptable range in PMV scale, particular following warm temperature experiences

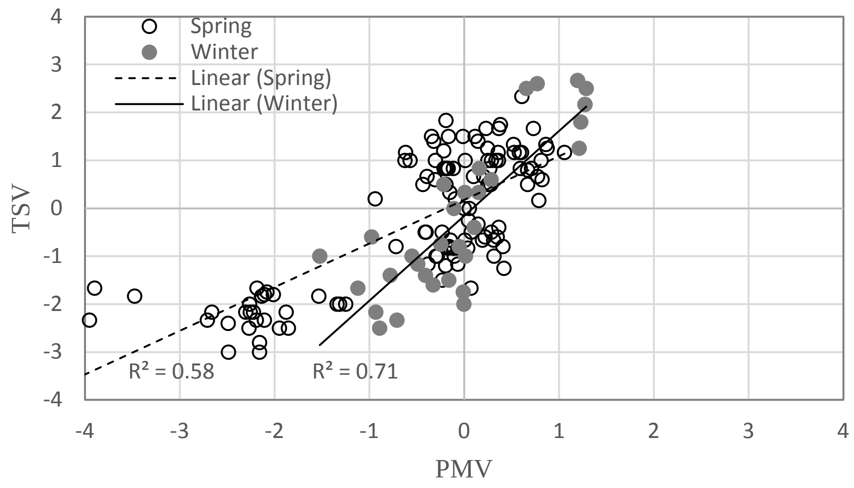

Figure 19 Participants' thermal sensation vote (TSV) reported immediately after transition versus the calculated values of PMV depicted separately for the spring (white dots, dashed regression line) and winter (black dots, continuous regression line) periods

In addition, the relationship between indoor air temperature and relatively expressed TSV of the thermally adapted participants, as well as the corresponding value of PMV model calculated using applicable clo value, were plotted for spring and winter periods respectively in Figure 20 and Figure 21. In the spring period, the dashed regression line of the PMV prediction was lower estimated than the actual TSV (black dots, continuous regression line) (r = 0.92, p < 0.01), particular in warmer temperatures, as the previous studies Beizaee et al. (2012) and Schiller (1990) with more tolerance for warmth. While in the winter period, the dashed regression line of the PMV prediction was constantly less estimated than the actual TSV (black dots, continuous regression line) (r = 0.92, p < 0.01). Referring to the Figure 18, it seems to reflect that the PMV value is lower predicted in the winter circumstances. Moreover, the neutral temperature of the thermally adapted participants found in the spring session was 23.3 ºC and 21.9 ºC in the winter session, which were respectively about 1.8 ºC lower and 0.4 ºC higher than those predicted using the PMV model.

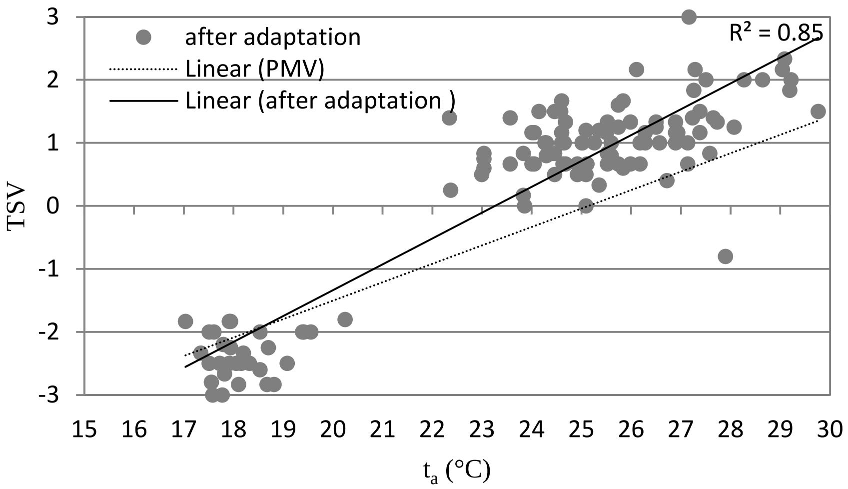

Figure 20 Thermal sensation vote (TSV) of thermally adapted participants (black dots, continuous regression line) and the calculated values of PMV (dashed regression line) as a function of indoor air temperature in the spring period

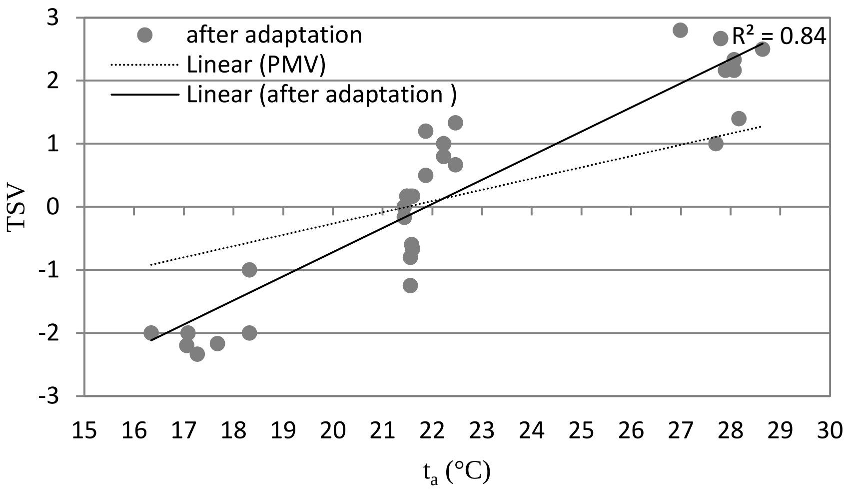

Figure 21 Thermal sensation vote (TSV) of thermally adapted participants (black dots, continuous regression line) and the calculated values of PMV (dashed regression line) as a function of indoor in the winter period

In our study, as stated in Figure 22, the 1.4 K discrepancy was found between the reported neutral temperatures in spring and winter periods, this suggesting that the average of clothing values were reported respectively 0.6 and 1.2 clo in spring and winter seasons (de Dear and Brager, 1998).

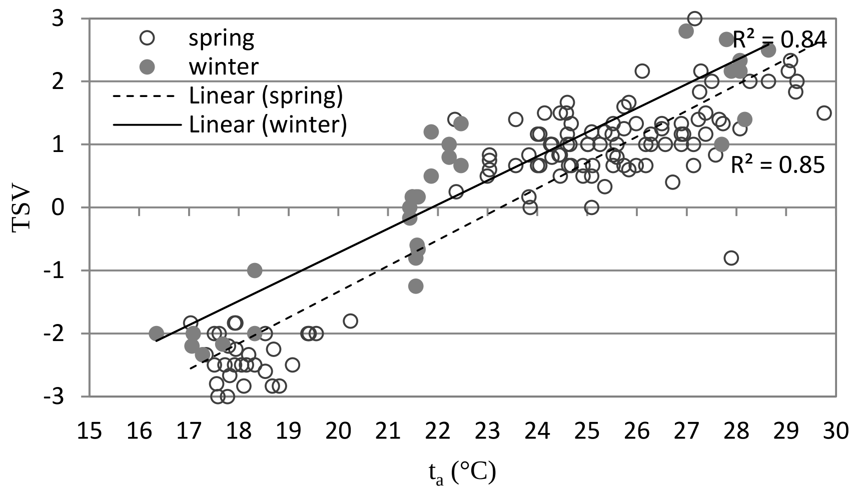

Figure 22 Relationship between thermal sensation vote (TSV) of thermally adapted participants and air temperature depicted separately for the spring (white dots, dashed regression line) and winter (black dots, continuous regression line) periods

Here, the relationship between indoor air temperature and expressed TSV of the thermally non-adapted participants, as well as expressed TSV of the thermally adapted participants, were also plotted for spring and winter periods respectively in Figure 23 and Figure 24. In the spring period, as compared with the continuous regression line in steady state, it can be observed that the dashed regression line (r = 0.80, $p < 0.01$) of participants' TSV in transitional states showed a larger range of higher temperature. However in the winter session, the dashed regression line (r = 0.82, $p < 0.01$) of participants' TSV expressed right after transition, which is parallel and quite close to the regression line of TSV expressed after adaptation.

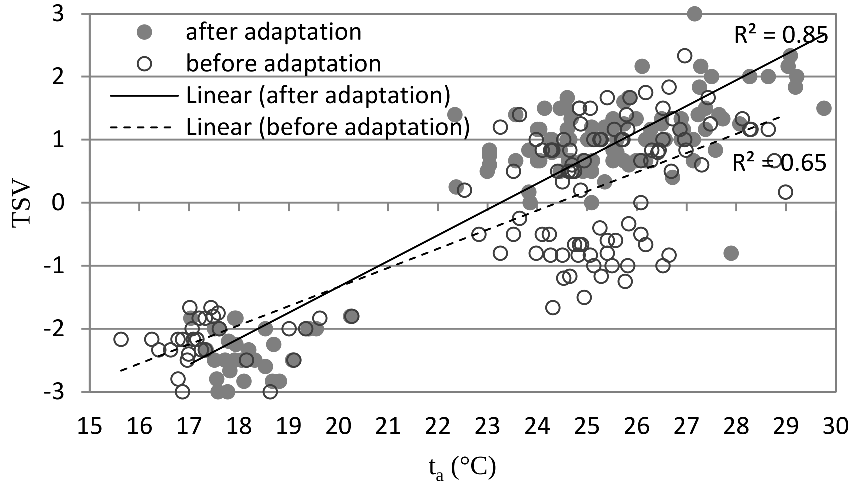

Figure 23 Relationship between air temperature and participants' sensation vote (TSV) expressed before (white dots, dashed regression line) and after (black dots, continuous regression line) adaptation in the spring period

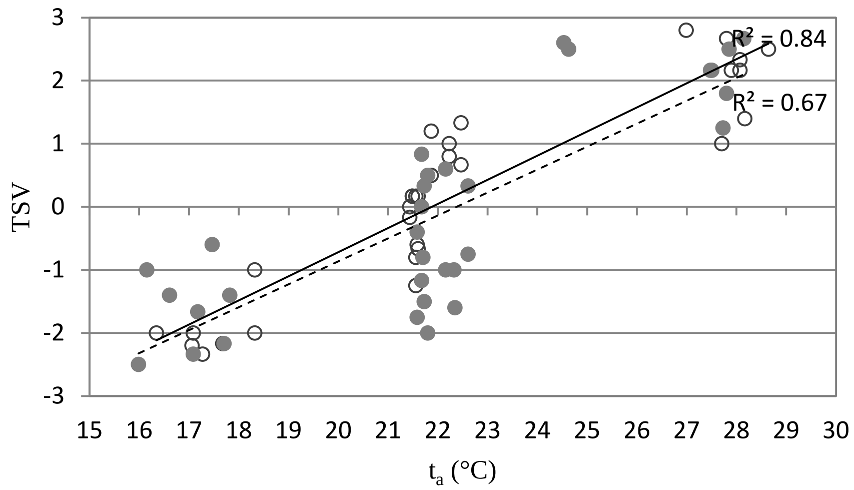

Figure 24 Relationship between air temperature and participants' sensation vote (TSV) expressed before (white dots, dashed regression line) and after (black dots, continuous regression line) adaptation in the winter period

4.1.2.3 Temperature differences

Figure 25 presents changes in thermal sensation vote (ΔTSV) after a spatial transition as a function of the temperature difference between the start room (θ_1) and the end room (θ_2). Thereby, ΔTSV denotes the difference between TSV immediately after transition (before adaptation) and before transition. Hence, increase in TSV is feeling warmer, whereas decrease in TSV is feeling cooler after a thermal transition. A non-linear regression line with high significant relationship (r = 0.95, p < 0.01) is observed between the change in expressed TSV and the temperature difference between the two rooms.

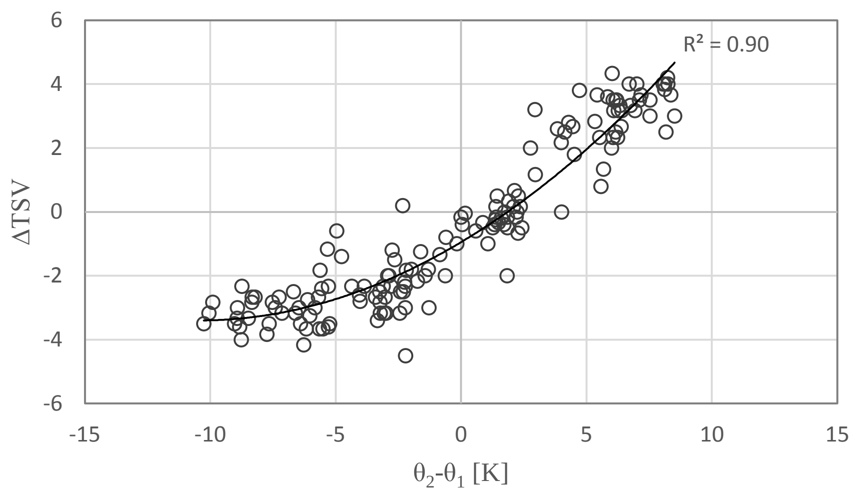

Figure 25 Change in thermal sensation vote (ΔTSV) following a spatial transition as a function of the temperature difference between the start room (θ_1) and the end room (θ_2) (all data)

These results suggest that changes in people's thermal sensation vote after a spatial transition (ΔPMV) could be estimated based on the difference in room temperatures (Δθ). Toward this end, the results of our study could be represented in terms of the following relationship (Eq. 9):

$$\Delta PMV = 0.02\,\Delta\theta^2 + 0.47\,\Delta\theta - 0.95 \qquad \text{Eq. 9}$$

Figure 26 is similar to Figure 25, but it presents the relationship between difference in the temperatures of the two rooms and the corresponding change in thermal comfort vote (ΔTCV). As this Figure clearly indicates and as opposed to the case thermal sensation vote, the relationship (r = 0.17, p < 0.01) between the change in the thermal comfort vote and temperature difference between the two rooms is rather weak.

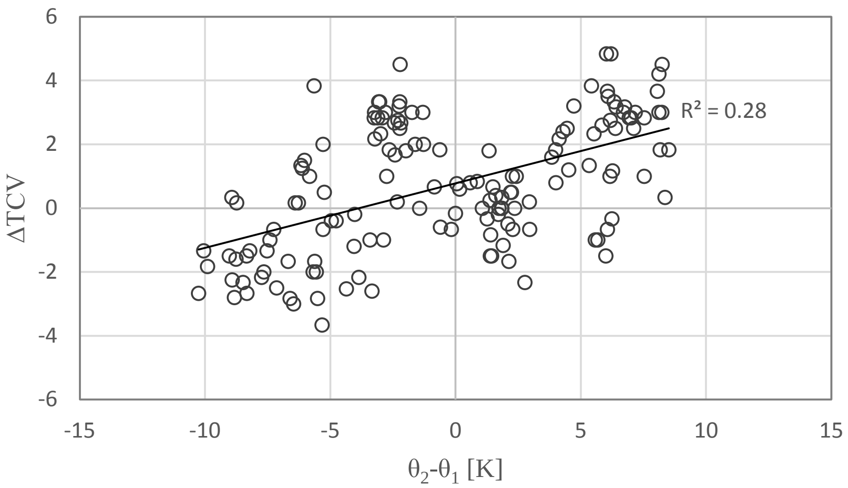

Figure 26 Change in thermal comfort vote (ΔTCV) following a spatial transition as a function of the temperature difference between the start room (θ_1) and the end room (θ_2) (all data)

Change in the thermal comfort vote, however, cannot be reliably predicted based on the temperature difference between the two rooms. To address this circumstance, as it could be expected, considering the effect of thermal experiences within a transition toward or away from thermal neutrality and the relationship between changes in the thermal comfort vote and the temperature of the room in which the participants arrived after the transition (θ_2).

4.1.2.4 Two categories of temperature change

Figure 27 shows, the same information in Figure 17, but the participants' post-transition TSV versus the corresponding calculated value of PMV were divided into 2 categories: immediate responses after a spatial transition involving thermal experiences away from neutrality (write dots, dashed regression line) and after a spatial transition involving thermal experiences toward neutrality (dark dots, continuous regression line). It can be observed that the dashed regression line (r = 0.88, p < 0.01) of participants' TSV expressed initially after a transition away from the neutrality were quite similar to the PMV predicted for the new environment in steady state. However, following a transition toward thermally neutral conditions, their initial TSV expressions drifted or increased more than the PMV predicted. Thus, referring to Figure 16, in a lower temperature change within the transition toward a neutral condition, participants' expressed TSV would be initially under neutrality (TSV = 0) and then return to the new adapted thermal sensation vote.

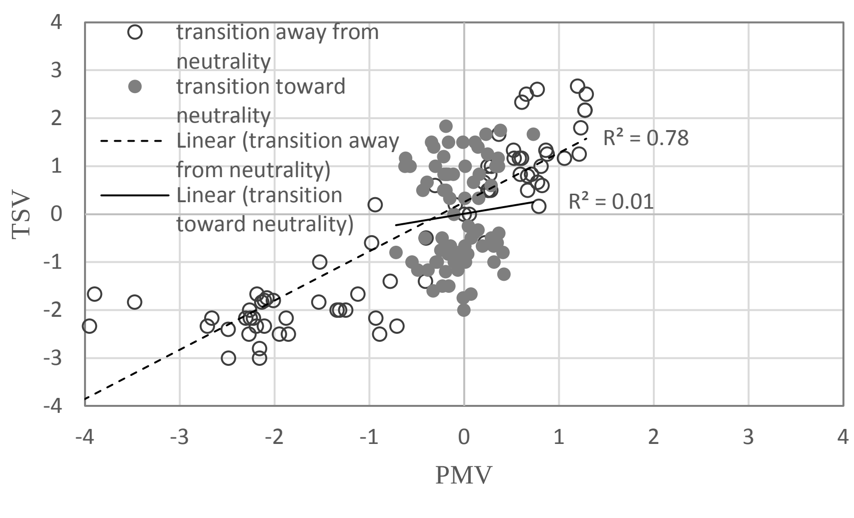

Figure 27 Participants' thermal sensation vote (TSV) immediately after transition versus the calculated values of PMV shows the transition involving thermally experiences away from neutrality (white dots, dashed regression line) and toward neutrality (dark dots, continuous regression line) respectively

Figure 28 shows the change in thermal sensation vote (ΔTSV) immediately after transition versus the corresponding change of calculated values in PMV including the transition involving thermally experiences away from neutrality (write dots, dashed regression line) and toward neutrality (dark dots, continuous regression line) respectively. The continuous regression line (r = 0.95, p < 0.01) presents a more pronounced change than the case move away from neutrality, indicating that the participants are much more sensitive to the thermal situation after a transition toward neutrality at initial stage (Du et al. 2014). In the other case, the dashed regression line (r = 0.87, p < 0.01) represents that, compared to the predicted change by PMV model, the change of expressed TSV was quite similar to the predicted value when entering a warmer environment, relatively indicating participants were more sensitive to colder changes.

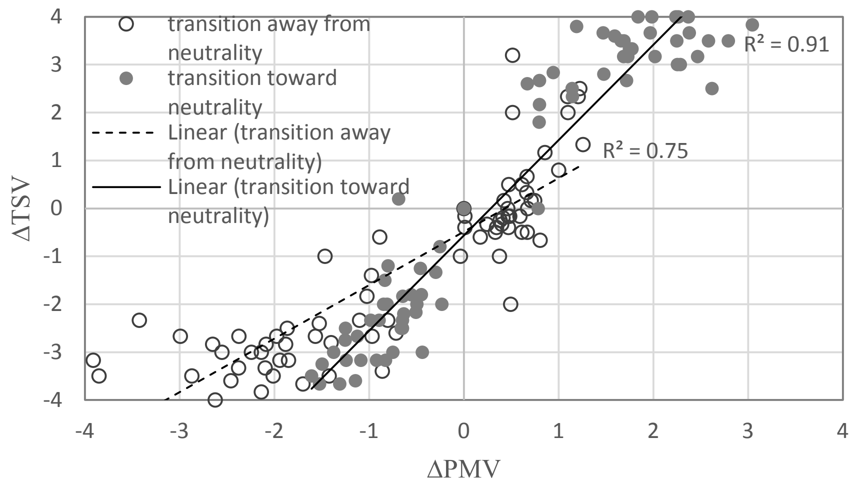

Figure 28 Change in thermal sensation vote (ΔTSV) immediately after transition versus the corresponding change of calculated values in PMV shows the transition involving thermally experience away from neutrality (write dots, dashed regression line) and toward neutrality (dark dots, continuous regression line) respectively

Figure 29 shows the same information as Figure 25, but in this case the change of expressed TSV following a spatial transition as a function of the temperature difference shows the transition involving thermally experiences away from neutrality (write dots, dashed regression line) (r = 0.91, p < 0.01) and the transition involving thermally experiences toward neutrality (dark dots, continuous regression line) (r = 0.96, p < 0.01) respectively. Both regression functions present good correlation and reflect the difference of expressed TSV change in the different conditions, which seems to explain the non-linear regression line in Figure 25.

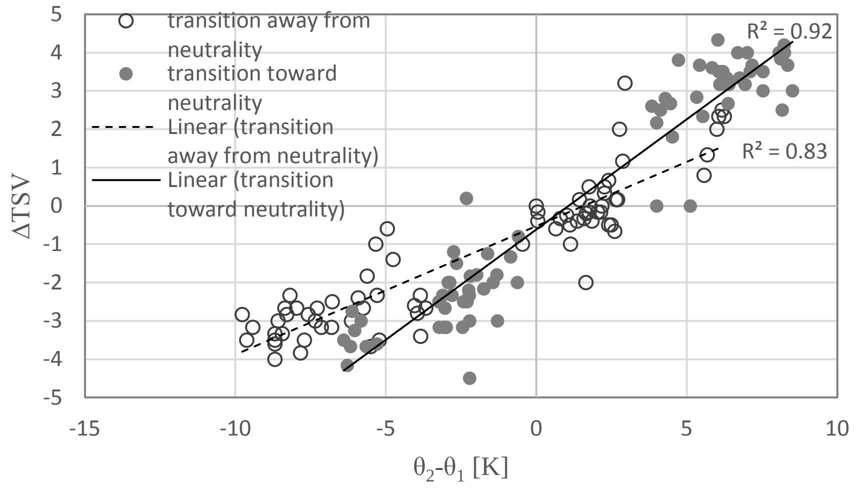

Figure 29 Change in thermal sensation vote (ΔTSV) following a transition as a function of the temperature difference shows the transition involving thermally condition away from neutrality (write dots, dashed regression line) and toward neutrality (dark dots, continuous regression line) respectively

These results suggest that changes in people's thermal sensation vote after a spatial transition (ΔPMV) considering the different conditions of transition, away from neutrality or toward neutrality, could be estimated based on the difference in room temperatures (Δθ). Toward this end, the results of our study could be represented in terms of the following relationship for the transition away from neutrality (Eq. 10) and toward neutrality (Eq. 11):

$$\Delta PMV = 0.01\,\Delta\theta^2 + 0.39\,\Delta\theta - 0.79 \qquad \text{Eq. 10}$$

$$\Delta PMV = 0.01\,\Delta\theta^2 + 0.56\,\Delta\theta - 0.76 \qquad \text{Eq. 11}$$

4.1.2.5 Post-transition comfort temperature

Figure 30 consists of the corresponding data for the spring (white dots, dashed regression function) and winter (black dots, continuous regression function) periods. While the respective correlations are not strong, they do point to a Spring-Winter shift in post-transition temperature values associated with largest improvements in thermal comfort vote. Taking the thermal resistance of the participants' clothing into account, the recommend comfort temperature values (θ_c) (de Dear and Brager, 1998) amount to about 24ºC for spring and 23ºC for winter, consistent with the peaks of the regression curves in Figure 30.

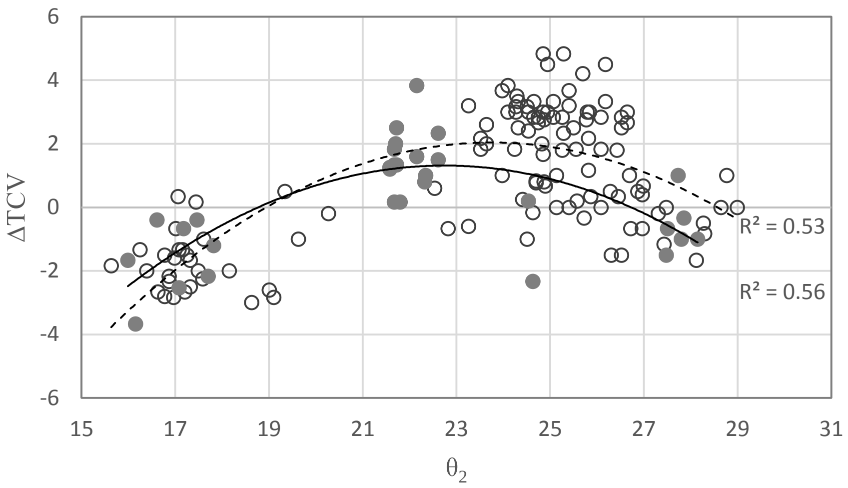

Figure 30 Change in the thermal comfort vote (ΔTCV) as a function of the post-transition room temperature (θ_2) shown separately for the spring (white dots, dashed regression function) and winter (black dots, continuous regression function) periods

We can thus speculate that in the course of a spatial transition, people display a higher TCV, if the temperature converges toward comfort temperature. In contrast, if the transition involves a divergence from comfort temperature, we should expect a decrease in TCV. To further pursue this matter, we categorized all 782 individually experienced transitions in the experiments in terms of 6 categories (see Table 13) according to the position of start and end temperatures (θ_1, θ_2) with regard to comfort temperature (θ_c).

Table 13 Categorization of (indoor to indoor) transition categories experienced by participants according to the position of start and end temperatures (θ_1, θ_2) with regard to comfort temperature (θ_c)

Category	θ_1	θ_2	$\theta_2 - \theta_1$ [K]
A	$< \theta_c$	$< \theta_c$	> 0
B	$> \theta_c$	$> \theta_c$	< 0
C	$< \theta_c$	$< \theta_c$	< 0
D	$> \theta_c$	$> \theta_c$	> 0
E	$< \theta_c$	$> \theta_c$	> 0
F	$> \theta_c$	$< \theta_c$	< 0

Figure 31 (Spring period) and Figure 32 (Winter period) show, for the six transition categories of Table 13, the changes in temperature (dashed vector) together with the corresponding changes in expressed TSV (black vector) and TCV (gray vector). As it could be expected, the information in this figure implies that the direction of changes in TSV after a transition are consistent with the direction of changes in temperature. The direction of TCV change, however, may point in the opposite direction of temperature change (B, D in Figure 31, E and F in Figure 32). If as a result of transition the distance to the comfort temperature is increased, TCV change is negative. Otherwise, the TCV change is positive.

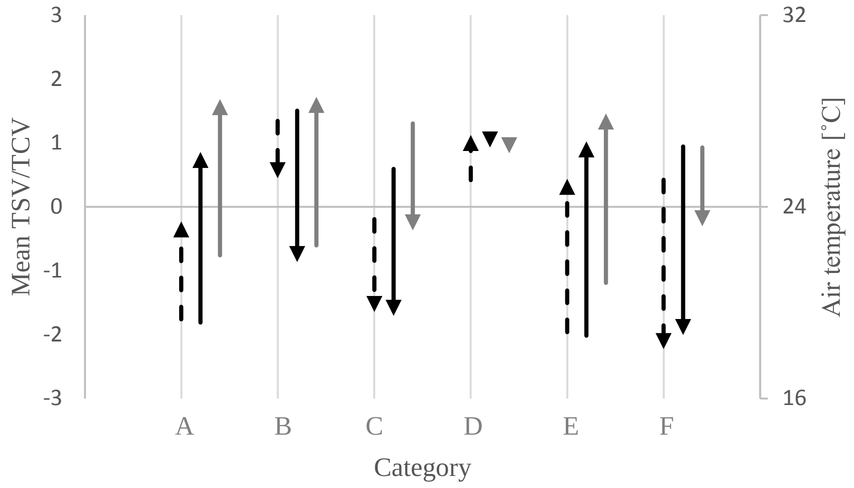

Figure 31 The changes in temperature (dashed vector) together with the corresponding changes in expressed TSV (black vector) and TCV (gray vector) for the six transition categories of Table 13 (Spring)

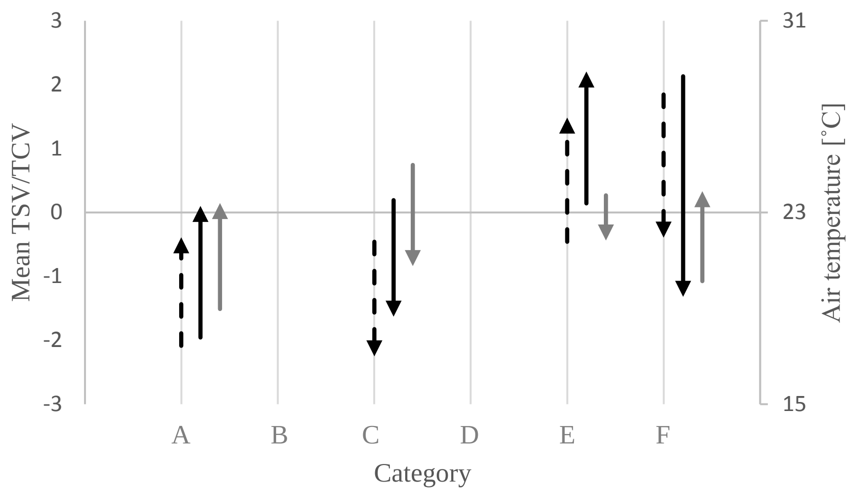

Figure 32 The changes in temperature (dashed vector) together with the corresponding changes in expressed TSV (black vector) and TCV (gray vector) for the six transition categories of Table 13 (Winter)

4.1.2.6 Effective temperature difference

To further investigate this point, proposing the concept of an effective temperature difference ($\Delta\theta_{eff}$), which denotes the transition-related net thermal distance (expressed in terms of temperature difference) to comfort temperature. It can be calculated as per the following equation (Eq. 12):

$$\Delta\theta_{eff} = |\theta_1 - \theta_c| - |\theta_2 - \theta_c| \qquad [K] \qquad \text{Eq. 12}$$

As the corresponding results depicted in Figure 33 suggest, there is a clear relationship between the effective temperature difference ($\Delta\theta_{eff}$) and the change in the thermal comfort vote after a thermal transition. Taking the effect of people's clothing into account (thermal resistance of clothing expressed in units of clo), the analyses of our data leads to a simple relationship to estimate the change in people's thermal comfort vote as a result of a spatial transition involving the effective temperature difference ($\Delta\theta_{eff}$). This relationship can be expressed (for the clo range of 0.5 to 1.5 and $\Delta\theta_{eff}$ range of -5 to +5 K) in terms of the following equation (Eq. 13):

$$\Delta TCV = 0.3(\Delta\theta . clo^{-1} - 5clo + 6) \qquad \text{Eq. 13}$$

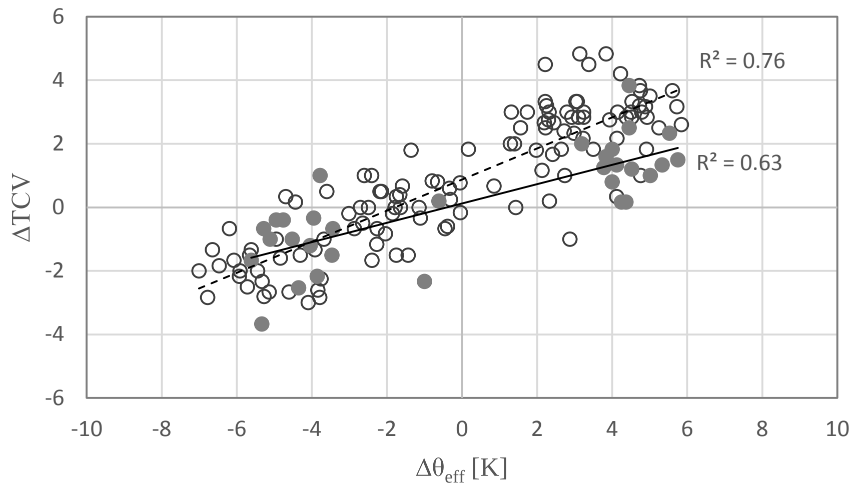

Figure 33 Change in thermal comfort vote (ΔTCV) following a spatial transition as a function of effective temperature difference ($\Delta\theta_{eff}$) [K] shown separately for the spring (white dots, dashed regression function) and winter (black dots, continuous regression function) periods

4.2 Results of field study

Figure 34 shows a comparison between participants' expressed thermal sensation vote (TSV) immediately after a spatial transition (before adaptation) and corresponding calculated PMV values. The observed regression line indicates that the range of participants' TSV evaluations following a transition is much larger than the PMV predicted. Moreover, TSV expressions immediately after transition include values below zero (indicating cold perception), whereas the corresponding PMV values are all above 0. These results indicate the PMV prediction may not appropriate for participants' TSV evaluation immediately after a transition.

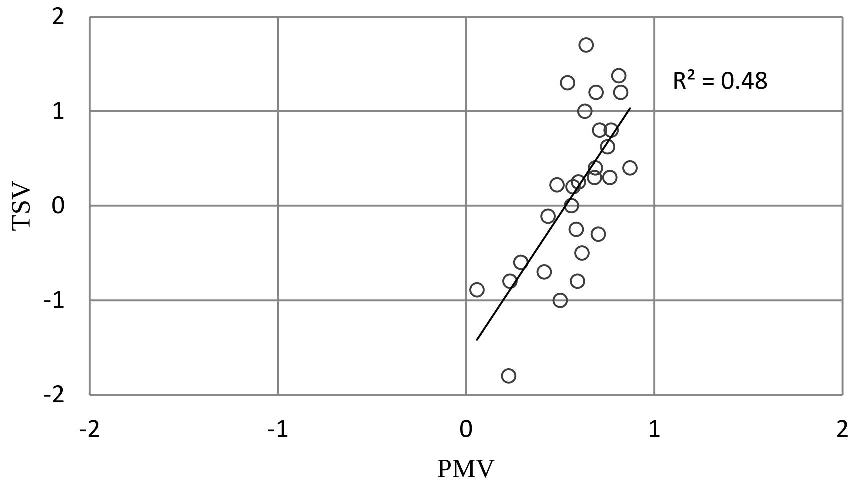

Figure 34 Participants' thermal sensation vote (TSV) immediately after transition versus calculated values of PMV

Figure 35 shows the change in thermal sensation vote (TSV_2-PMV_1) following a spatial transition as a function of the temperature difference between the start and end rooms (θ_2 – θ_1). Thereby, TSV_2-PMV_1 denotes the differences between participants' thermal sensation vote immediately after transition (before adaptation) and before transition. Hence, increase in TSV is positive, whereas, decrease in TSV is negative. Note that TSV_2 is based on reported user expression, but PMV_1 values were calculated (based on conditions in the start room). The results show a good correlation between the change in thermal sensation vote and the temperature difference between the two rooms even through the temperature differences are relatively small. Moreover, as with the results shown in Figure 34, changes in thermal sensation vote are larger than the corresponding changes in calculated PMV values.

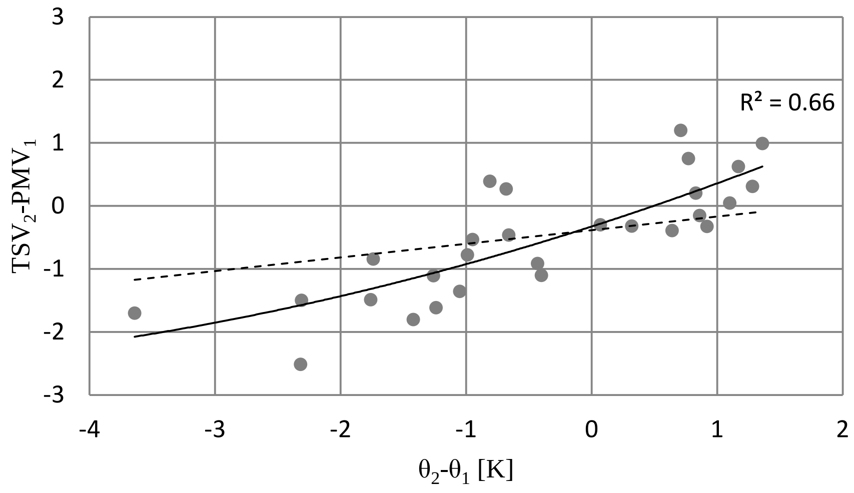

Figure 35 The change in thermal sensation vote (TSV_2-PMV_1) following a spatial transition as a function of the temperature difference between the start room (θ_1) and the end room (θ_2). The change in the calculated PMV before and after transition is also shown as a function of temperature difference (dashed line)

These results appear to be in agreement with the similar finding in one of our previous studies involving experiments under controlled laboratory setting (Wu and Mahdavi, 2014). The results of this laboratory study suggested that changes in people's thermal sensation vote after a spatial transition could be estimated base on the difference in room temperatures using the following relationship (Eq. 13).

Figure 36 shows a comparison between the empirical results (Figure 35) and corresponding calculations using Eq. 13. As this Figure shows, calculated results using Eq. 13 (dashed line in Figure 36) agree in tendency with experimental results presented in this paper, but are consistently lower.

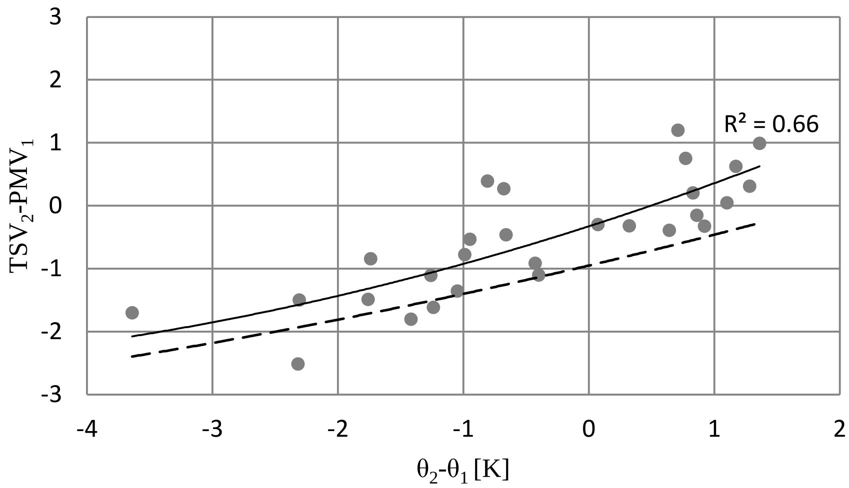

Figure 36 The change in thermal sensation vote (TSV_2-PMV_1) (black dots, continuous regression function) and the change in thermal sensation vote based on the (Eq. 13) (dashed regression function) following a spatial transition as a result of the temperature difference

5 Discussion

Results of laboratory study

As stated before, we documented participants' thermal sensation vote (TSV) and thermal comfort vote (TCV) before transition from one room to another, immediately after a spatial transition with thermal differences, and after a brief period of adaptation.

Corresponding PMV values were calculated using applicable clo-values and a general value of 1.2 MET for activity. PMV values correlated better with post-adaptation TSV values as compared to post-transition TSV values displayed in Figure 17. This is expressed in a coefficient of determination of 0.74 in the former case versus one of 0.56 in the latter case. This result is consistent with the nature of standard calculation methods for PMV, as they are geared toward thermally adapted people. Consequently, the comparison of post-transition TSV expressions with the PMV values is strictly speaking not applicable. The comparison is included here nonetheless, as the general familiarity of the PMV (and its associated definition and calculation methods) provides a basis to situate the results in a broader context. Moreover, future practical applications of transitional thermal comfort theory could conceivably facilitate the understanding of comfort implications of transition processes using deviation terms from – or modification factors to – the PMV calculations (or other indicators pertaining to thermal comfort of adapted individuals).

Note that the transitions in our experiment involved only a very short walking distance. Nonetheless, it is conceivable that the activity level might have slightly increased in the course of transition. However, the PMV calculations with increased MET values would still not provide a proper comparison basis to TSV expressions of non-adapted participants. Moreover, the PMV calculations involving higher values for MET would not explain the PMV versus TSV discrepancy in the present case. In fact, higher MET assumptions in the PMV calculations would increase the discrepancy between PMV and post-transition TSV (see Figure 17 and Appendix D), as the corresponding regression function (dashed line) would move further to the right.

In our study, the relationship between expressed TSV and calculated PMV values shows noteworthy differences between winter and spring experiments. Specifically, the steeper slope of the regression line for winter data (see Figure 18) suggests a more pronounced thermal response of the participants to the prevailing temperatures and – as compared to PMV-based predictions – a narrower tolerance range in view of thermally acceptable indoor conditions. Note that this observation also applies to the responses of non-adapted participants (see Figure 19), as in this case too we observe a steeper slope of the regression line for winter data. Referring to Figure 21, it showed that the estimated PMV value was constantly lower than actual TSV of adapted occupants in a given environment in winter. However Figure 22 showed consistent discrepancy due to different clo values that were applied between spring and winter data, it seems to suggest that the PMV value is lower predicted particular in the winter circumstances (Beizaee et al. 2012; Oseland, 1994; Schiller 1990).

A further noteworthy observation can be drawn from the data displayed in Figure 16 and Figure 17. All dots in Figure 17 with a TSV value of less than zero pertain to transition cases involving a temperature decrease. A comparison of this data to Figure 16 suggests that participants experiencing the temperature drop evaluated the conditions to be cooler than PMV-based expectations would suggest. This discrepancy is mostly resolved after adaptation. This observation appears to be in agreement with Chen et al. (2011)'s findings concerning people's thermal sensation expressions after a spatial transition involving a temperature drop (28 to 24 ºC, 32 to 24 ºC). In such cases, the initial post-transitional TSV expressions were lower that the subsequent evaluations in adapted situation. In contrast, TSV expressions immediately after entering a warmer room (20 to 24 ºC) were not higher than subsequent evaluations in adapted situation. Besides, the results significantly in Figure 27, including two different transitional conditions presented separately between expressed TSV of post-transition participants versus the corresponding calculated PMV, seem to reflect the previous findings suggesting in a transition involving thermally experience away from neutrality, the immediate expression of participants would be similar to the PMV suggested. In contrast, after a transition involving a lower temperature experience toward neutrality, the immediate expression of participants would be initially under neutrality (TSV=0) and then return to the newly adapted thermal sensation.

The data analysis also revealed the relationship between the expressed TSV of adapted participants and the corresponding PMV against indoor air temperature variation. The neutrality temperature was suggested to be about 1.8ºC lower than that the PMV model predicted in the spring period (see Figure 20). However, the neutrality temperature in the winter period in our study was found to be close to that PMV model predicted (see Figure 21). This result is conceived to reflect that the neutral temperature in the spring session was conducted in a naturally ventilated space and the winter session was conducted in a conditioned space, which is in agreement with the studies suggesting the neutral temperature is correlated better in conditioned buildings (Humphreys and Nicol, 2002), whereas the neutral temperature is over predicted by the PMV model in naturally ventilated buildings as much as 3.6 K (Oseland, 1996).

An important component of our study related to the nature of contributing factors to the changes in thermal sensation vote subsequent to participants' transition between rooms of different temperature. In this context, the temperature difference between the two rooms is an obvious candidate for investigation. Based on the valid correlation between (Fishman and Pimbert 1979; Newsham and Tiller 1995) and also our data (see Figure 20 and Figure 21) show a high correlation between thermal sensation of thermally adapted participants and temperature variation, even though a wider distribution of expressed TSV was found immediately after transition which involved a lower thermal experience toward neutrality (see Figure 23 and Figure 24), the regression function between change in expressed TSV and the temperature difference is consistent. One related observation pertains to the non-linear regression function of Figure 25, which depicts a highly significant relationship between change in expressed TSV and the temperature difference between the two rooms. The experimental data depicted in Figure 25 provides the basis for a simple function (Eq. 9) for the prediction of changes in people's thermal sensation vote after a spatial transition ($TSV_2 – TSV_1$) based on the difference in room temperatures ($\theta_2 – \theta_1$).

A non-linear regression was found in two different transitional conditions: after a spatial transition involving thermal condition toward neutrality, it would be more sensitive (larger change in TSV) to participants (Du et al.2014) than after a spatial transition which involved thermal condition away from neutrality (see Figure 28). This result is consistent with the finding (Gagge et al., 1967) that considered the effects of transition in different thermal change conditions. The experimental data depicted in Figure 29 provides the functions (Eq. 10 and Eq. 11) for the prediction of changes in people's thermal sensation vote after a spatial transition ($TSV_2 – TSV_1$) based on the difference in room temperatures ($\theta_2 – \theta_1$), but considering the two different transitional conditions respectively.

With regard to change in expressed thermal comfort vote (TCV_2-TCV_1) and the temperature difference between the two rooms ($\theta_2 – \theta_1$) involved in transition, a strong relationship could not be demonstrated. In fact, as it could be expected, the change in TCV immediately after a transition did not consistently follow the temperature difference pattern. Rather, it was found to be consistent with a proposed new measure "effective temperature difference ($\Delta\theta_{eff}$)", which denotes the transition-related net thermal distance (expressed in terms of temperature difference) to comfort temperature (see Eq. 12). This finding is consistent with Nakano's result (2003) concerning the relationship between changes in thermal comfort vote and changes in thermal sensation vote. Nakano suggested that transitions involving large temperature steps towards thermal neutrality (25 ºC) result in a correspondingly large improvement of thermal comfort feedback.

Taking the effect of people's clothing into account (thermal resistance of clothing expressed in units of clo), the analysis of our data leads to a simple function (Eq. 13) to estimate the change in people's thermal comfort vote as a result of a spatial transition involving the effective temperature difference ($\Delta\theta_{eff}$). Using this equation, the improvement or worsening of people's thermal comfort evaluation (expressed in terms of TCV) due to movement between differentially tempered spaces of a building can be roughly estimated based on the thermal resistance of their clothing and the pertinent values of the effective temperature difference.

Our findings have also been applied to predict participants' thermal sensation and thermal comfort under transitional conditions in a field experiments which were conducted in the Museum of Art History (Kunsthistorisches Museum) in Vienna, Austria. The results suggest that occupants' TSV immediately after a spatial transition cannot be reliably predicted based on calculated PMV results. Specifically, the spread of actual TSV was found to be larger than those of calculated PMV. Moreover, the collected data displayed in Figure 36 suggest that a previously introduced relationship (Eq. 13) for the estimation of the change in people's thermal sensation vote after a spatial transition (as a function of the temperature difference between the rooms) can correctly reproduce the general tendency, but not the absolute values of the empirical findings. This may be due to the fact, that – as compared to the previous laboratory experiment – the temperature differences between the museum's different spaces were smaller.

The study could in turn support decisions regarding proper set point temperatures for different spaces in buildings. For example, most buildings include spaces for short-term intermediate use such as circulation spaces (e.g., corridors). Transitional thermal comfort findings have the potential to optimize thermal conditions in such spaces in view of both thermal comfort and energy efficiency (Chun et al., 2004). Consider, as an illustrative point in case, the corridor in an office floor. Assuming *i)* a given comfort temperature to be maintained in the office spaces and *ii)* applicable thermal resistance of the occupants, the range of preferable temperature in the corridor can be derived (in our case using Eq. 13 above) such that the change in the predicted TCV after an office-to-corridor transition is either positive or, if negative, not more than a certain – maximally allowable – range.

Limitation and future study

The study has examined the subjective evaluations of thermal transitions between rooms of different temperatures and proposed a method to predict a proper set point of temperature for a space regarding transitional states discussed above, however, in the context of a number of uncertainties and limitations involving common issues of measurement precision and accuracy. The measurements of indoor environmental conditions involved in the study went through appropriate rigorous instrumentation and quality checks. However, thermal resistance of participants' clothing could not be measured but was estimated based on visual inspection. Despite the careful process, detailed documentation, and comprehensive informational basis (extensive tables of garments' thermal resistance), errors cannot be entirely excluded. Another basic shortcoming of the study is the rather limited range of the participants' age and occupation (mostly younger students). Moreover, the model was conducted in laboratory setting in mock-up office rooms. Hence, the results may not be readily applicable to more realistic circumstances. As to the variance in outdoor climate, the experiments could only conduct during two distinct periods throughout the year (spring and winter). Moreover, it was not possible to recruit for the winter period the same – relatively large – number of participants as in the spring period.

To address these and other limitations in our future experiments, thereby, a more diverse sample of participants shall be studied both in laboratory and realistic settings. Empirical monitoring shall be further extended. Additional efforts will be needed to capture implications of changes in participants' activity levels (i.e., metabolic rates) in the course of spatial transition. Specifically, indoor air quality conditions shall be captured and considered in the analyses. Experiments shall be conducted on a regular basis throughout the year, encompassing thus a larger variety of outdoor conditions and clothing. Most importantly, future studies shall include spatial transitions from outdoor environment to indoor spaces and vice versa.

6 Conclusion

This thesis attempts to develop a method for setting a proper set point of temperature in a space regarding thermal comfort of occupants in transitional states thus to provide occupants a thermally continuously comfortable perception in a building.

Our findings generally suggest that participants' expressed TSV and corresponding PMV calculations are congruent. However, the values of participants' TSV in winter displayed a more pronounced value than the respective PMV values. This is true for evaluations both immediately after transition and after a short period of adaptation. These results appear to suggest that in winter, participants' tolerance range in view of acceptable indoor temperatures is narrower than the range suggested by PMV-based calculations. Furthermore, a significant difference was found between two different transitional conditions: the results showed that participants' TSV expressed immediately after a transition away from the neutrality were similar to the predicted value of PMV for the new environment in steady state. While following a transition toward thermally neutral conditions, their TSV expressions drifted and increased initially and resolved after a period of adaptation. Therefore, participants were found to be more sensitive when moving through a transition involving thermal experience toward neutrality.

The results of the study further suggest that the tendency of the change in participants' thermal sensation (expressed in terms of TSV) immediately after a transition was generally consistent with transition-related temperature differences. As for TCV, our results imply a noteworthy relationship reflects from the distance to comfort temperatures before and after transition (effective temperature difference). A corresponding significant correlation could be found between the transition-related effective temperature difference and the change in thermal comfort vote immediately after a transition. Hence, the net reduction (or increase) of distance to applicable comfort temperature appears to provide an expedient basis for the prediction of the change in people's expressed TCV immediately after a thermally relevant spatial transition.

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Appendix A

Laboratory study

Clothing value index of questionnaire.

Clothing		Clo Value	Check
Shirts	Turtleneck	0.05	☐
	Tube top	0.05	☐
	Short sleeves(T-shirt)	0.10	☐
	Long sleeves	0.25	☐
Trousers	Shorts	0.05	☐
	Normal trousers	0.25	☐
Skirts, dresses	Short skirt	0.02	☐
	Long skirt	0.20	☐
	Light dress sleeveless	0.25	☐
	Winter dress long sleeves	0.40	☐
Sweaters	Sleeveless vest	0.15	☐
	Thin sweater	0.25	☐
	Thick sweater	0.35	☐
Overcoat	Jacket	0.35	☐
	Coat	0.60	☐
Sundries	Socks	0.02	☐
	Thick long socks	0.10	☐
	Thin soled shoes	0.02	☐
	Thick soled shoes	0.04	☐
	Boots	0.05	☐
	Clo Value		

a. How do you describe your thermal perception right now?

-3	-2	-1	0	1	2	3
cold	cool	slightly cool	neutral	slightly warm	warm	hot

b. How comfortable do you feel thermally right now?

-3	-2	-1	1	2	3
very uncomfortable	uncomfortable	just uncomfortable	just comfortable	comfortable	very comfortable

c. How would you prefer to feel?

-1	0	1
prefer cooler	No change	prefer warmer

Thermal sensation vote (TSV), thermal comfort vote (TCV) and thermal preference vote (TPV) of questionnaire.

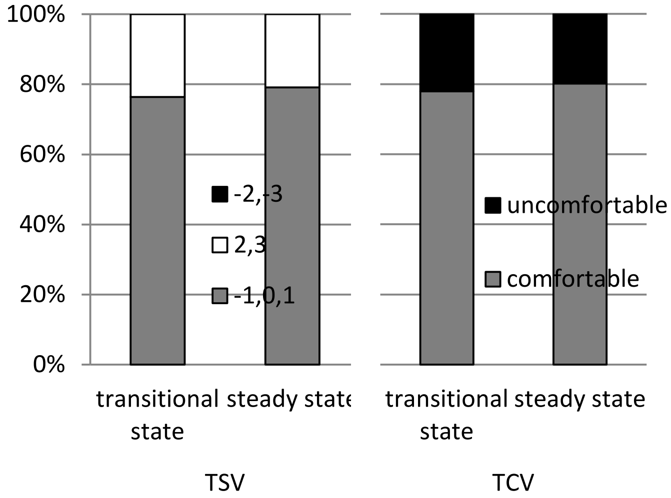
Appendix B

Statistical summary of environmental conditions for spring and winter periods respectively

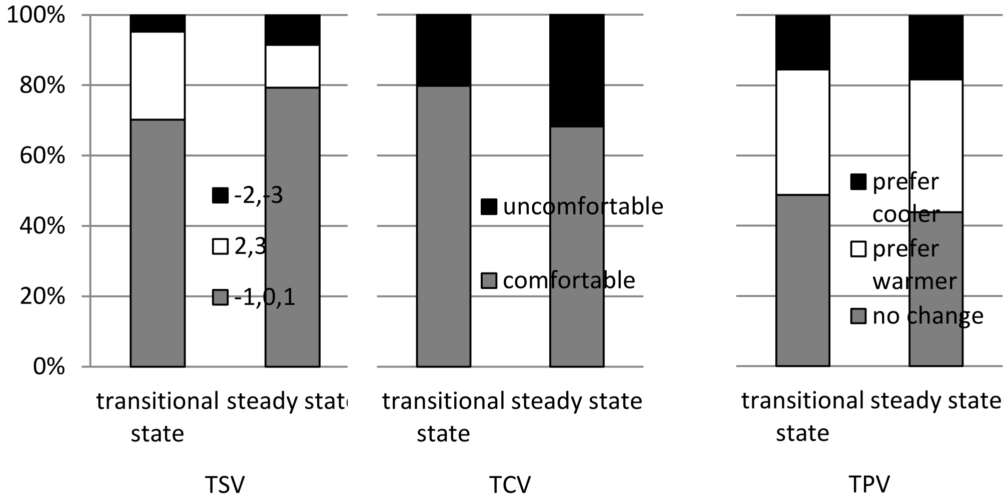
		Spring season				Winter season			
		Av.	S.D.	Max.	Min.	Av.	S.D.	Max.	Min.
Il (lx)	M	472.92	136.87	674.10	295.60	412.26	134.57	564.00	264.00
	A	327.33	25.56	358.70	272.00	483.89	73.81	603.00	398.00
	B	327.24	20.16	350.80	264.10	622.56	65.53	713.00	509.00
CO_2 (ppm)	A	703.86	215.88	1384.00	496.90	688.56	135.11	1096.00	581.00
	B	938.14	303.74	1605.00	487.80	820.50	240.04	1220.00	486.00

Av. = average over entire group; S.D. = standard deviation; Max., Min. = maximal and minimal recorded values; Il = Illuminance; CO_2 = Carbon dioxide measured at seated height

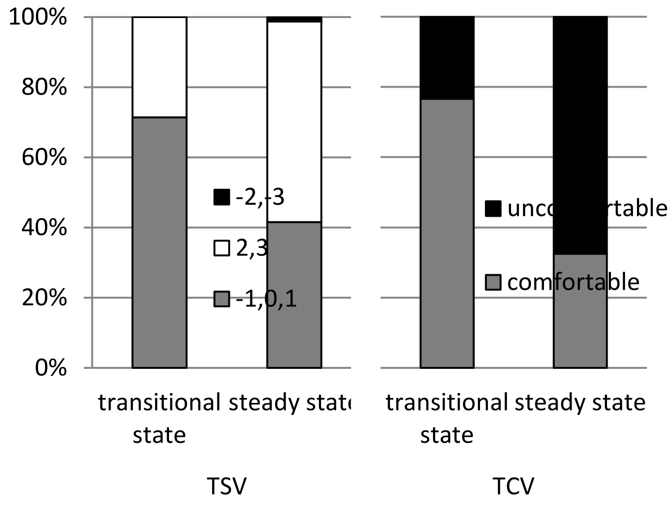
Appendix C



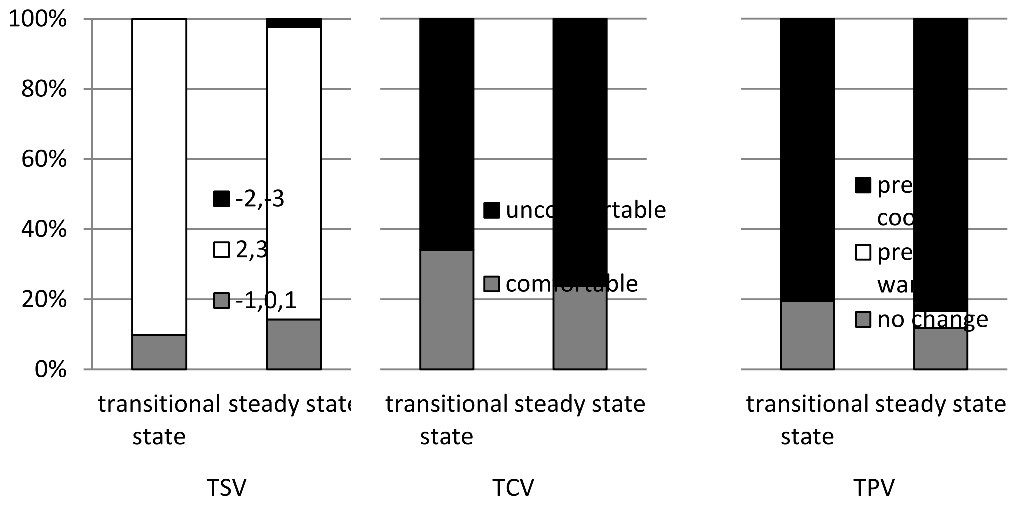
Thermal sensation vote (TSV) and thermal comfort vote (TCV) responses between transitional states and steady states of transition E-M in the spring period



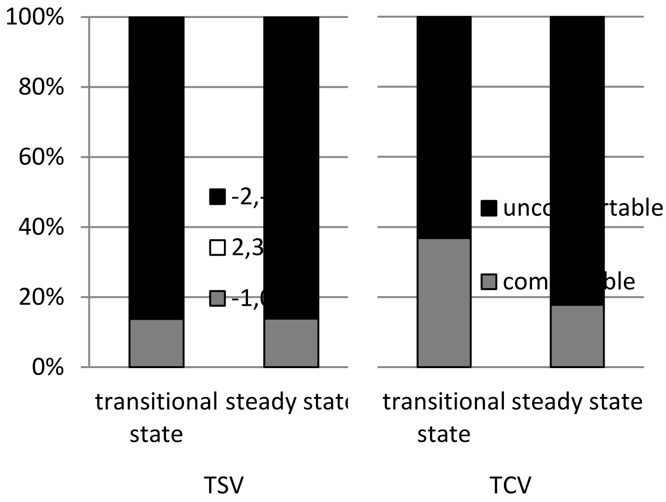
Thermal sensation vote (TSV) and thermal comfort vote (TCV) and thermal preference vote (TPV) responses between transitional states and steady states of transition E-M in winter period



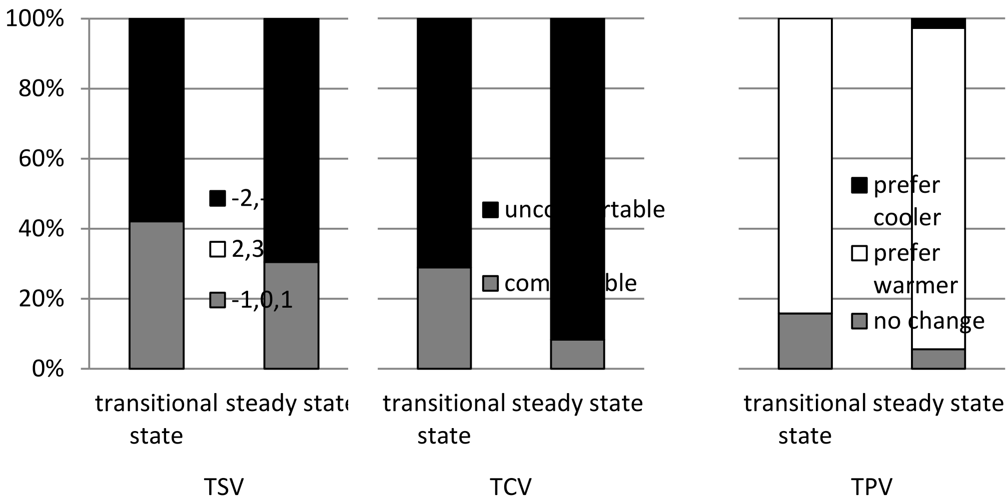
Thermal sensation vote (TSV) and thermal comfort vote (TCV) responses between transitional states and steady states of transition M-A in the spring period



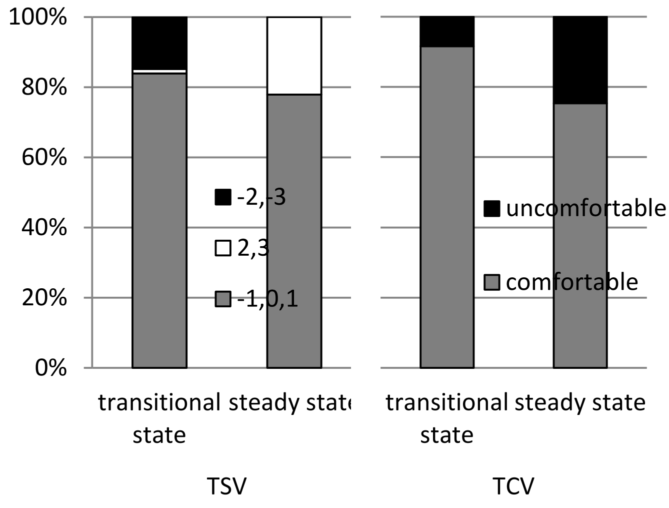
Thermal sensation vote (TSV) and thermal comfort vote (TCV) and thermal preference vote (TPV) responses between transitional states and steady states of transition M-A in winter period



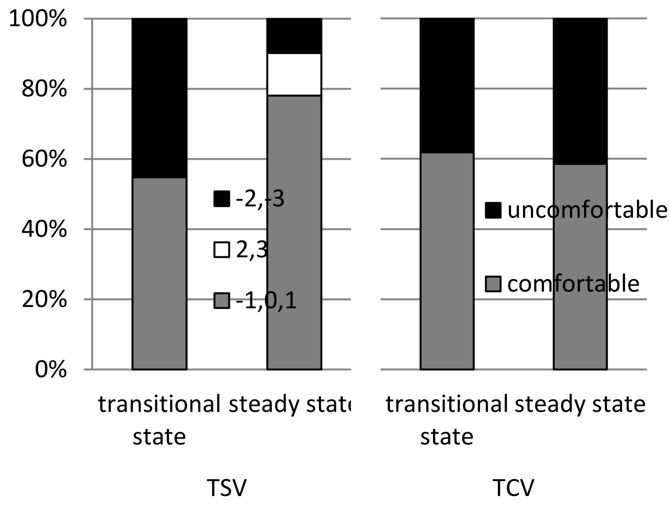
Thermal sensation vote (TSV) and thermal comfort vote (TCV) responses between transitional states and steady states of transition M-B in the spring period



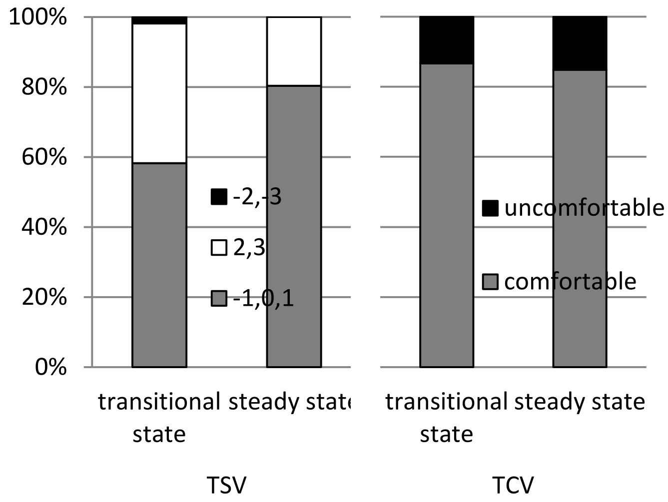
Thermal sensation vote (TSV) and thermal comfort vote (TCV) and thermal preference vote (TPV) responses between transitional states and steady states of transition M-B in winter period



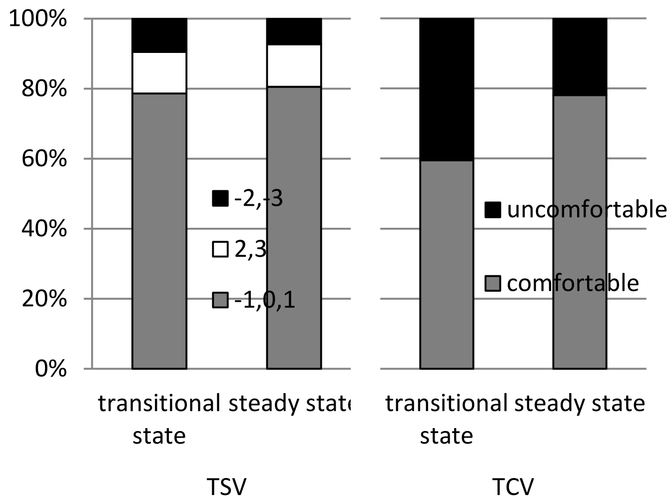
Thermal sensation vote (TSV) and thermal comfort vote (TCV) responses between transitional states and steady states of transition A-M in the spring period



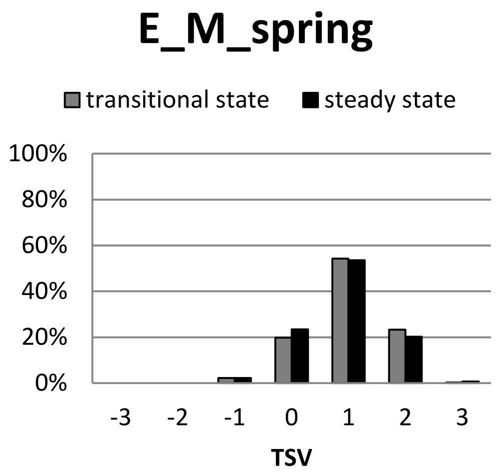
Thermal sensation vote (TSV) and thermal comfort vote (TCV) responses between transitional states and steady states of the transition A-M in the winter period

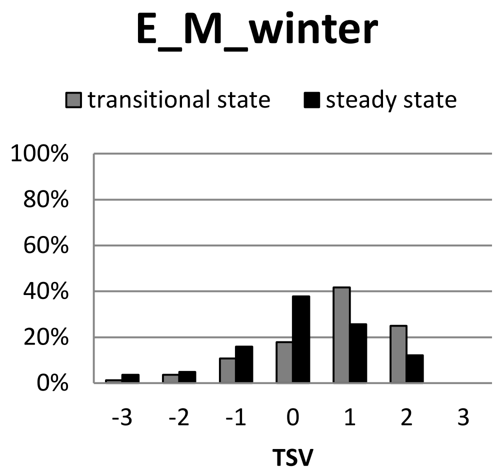


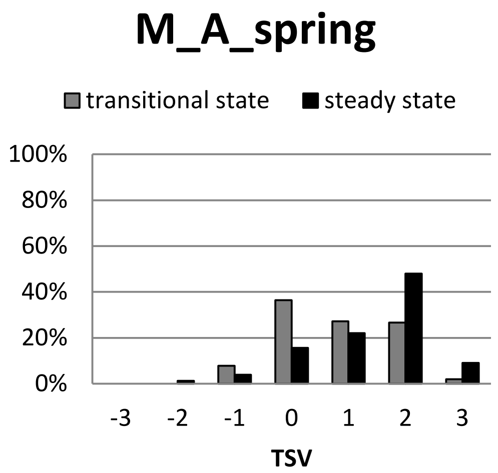
Thermal sensation vote (TSV) and thermal comfort vote (TCV) responses between transitional states and steady states of transition B-M in the spring period

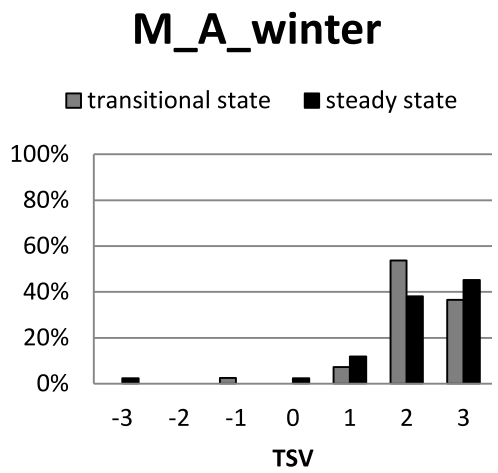


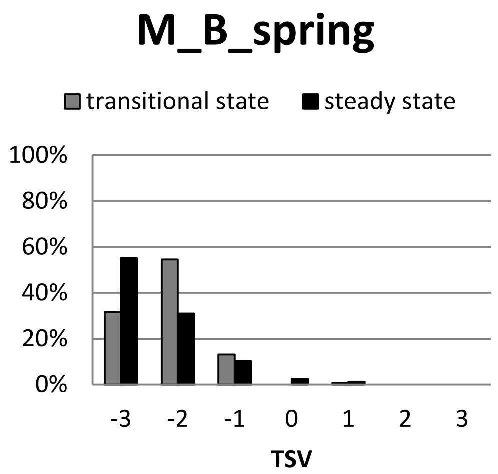
Thermal sensation vote (TSV) and thermal comfort vote (TCV) responses between transitional states and steady states of the transition B-M in the winter period

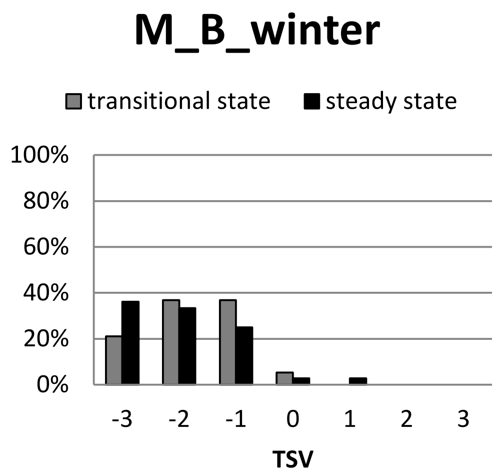

E_M_spring
transitional state
steady state
100%
80%
60%
40%
20%
0%
-3 -2 -1 0 1 2 3
TSV

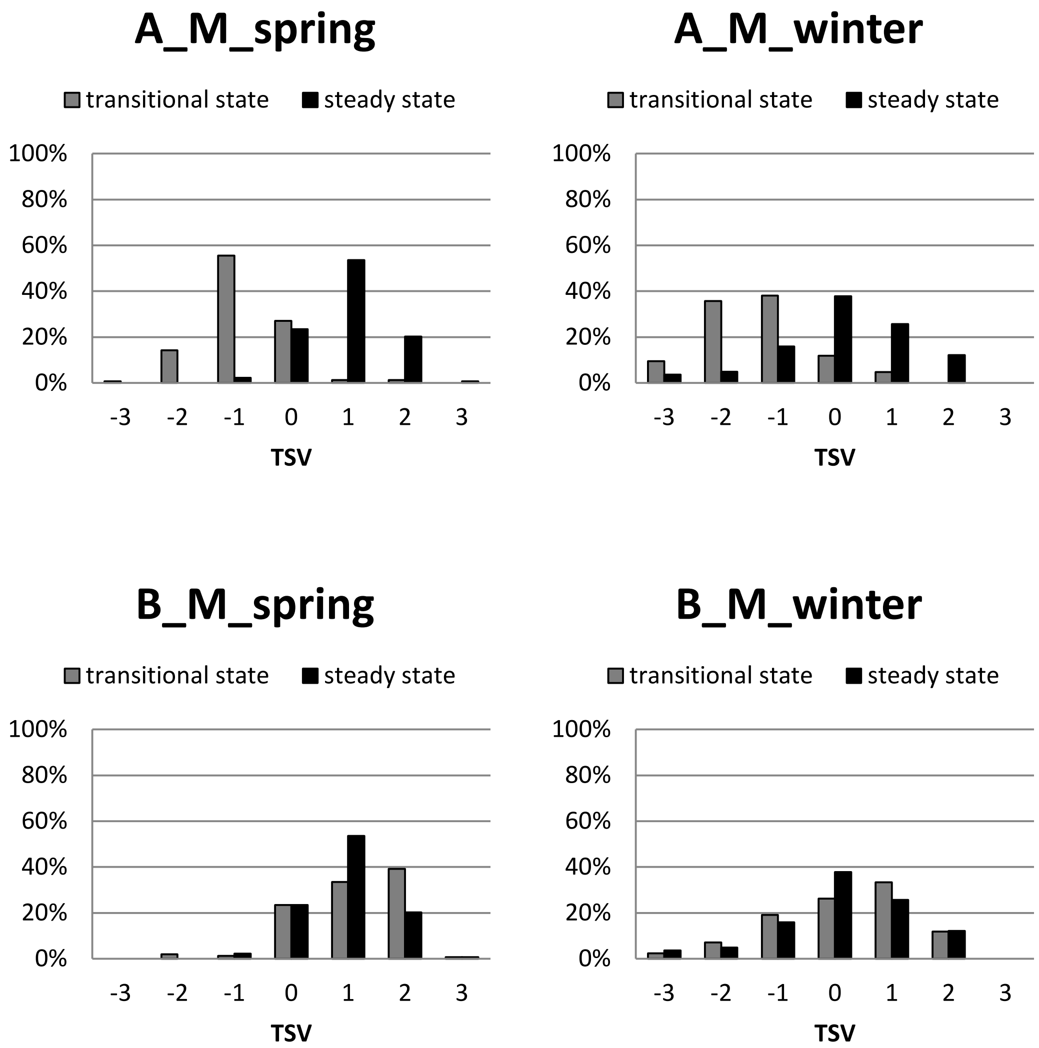

E_M_winter
transitional state
steady state
100%
80%
60%
40%
20%
0%
-3 -2 -1 0 1 2 3
TSV


M_A_spring
transitional state
steady state
100%
80%
60%
40%
20%
0%
-3 -2 -1 0 1 2 3
TSV


M_A_winter
transitional state
steady state
100%
80%
60%
40%
20%
0%
-3 -2 -1 0 1 2 3
TSV

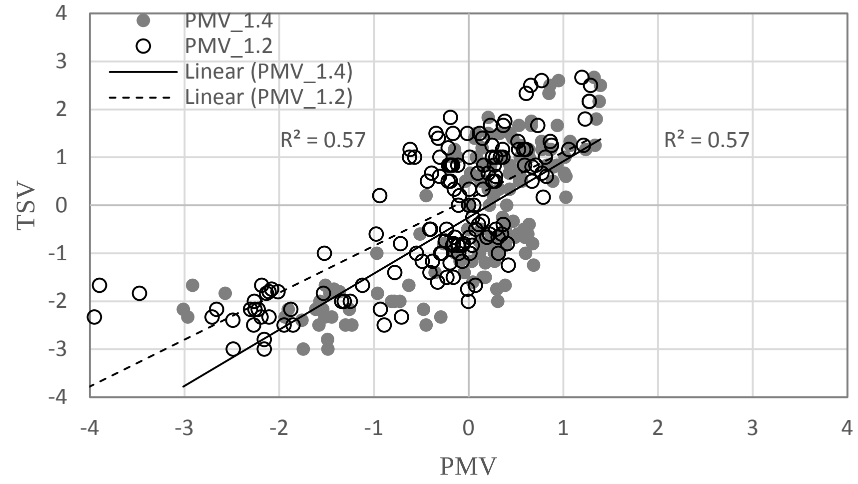

M_B_spring
transitional state
steady state
100%
80%
60%
40%
20%
0%
-3 -2 -1 0 1 2 3
TSV


M_B_winter
transitional state
steady state
100%
80%
60%
40%
20%
0%
-3 -2 -1 0 1 2 3
TSV

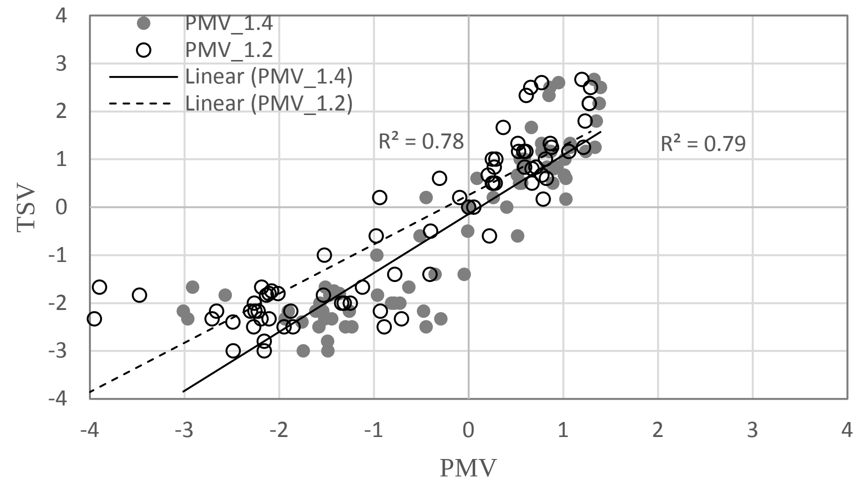


Distribution of thermal sensation vote (TSV) responses before and after adaptation following a transition for the spring and winter periods respectively

Appendix D



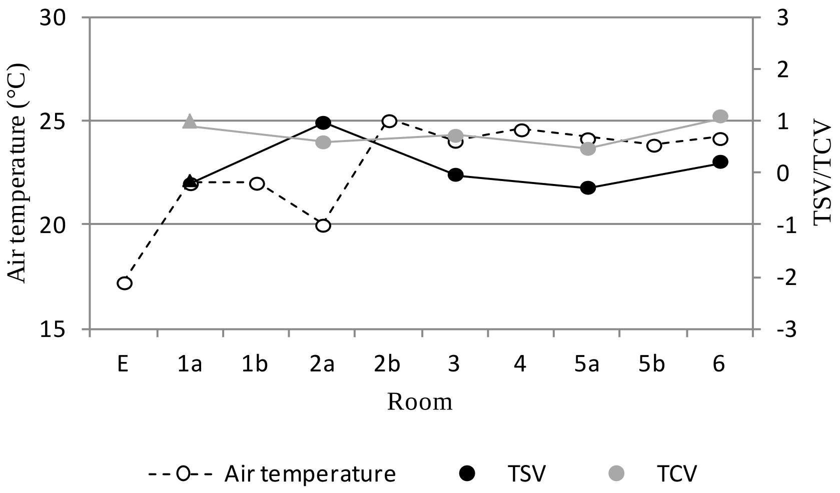
Participants' thermal sensation votes (TSV) reported immediately after the transition versus the calculated PMV value for met =1.2 (white dots, dashed regression line) and met = 1.4 (black dots, continuous regression line) separately

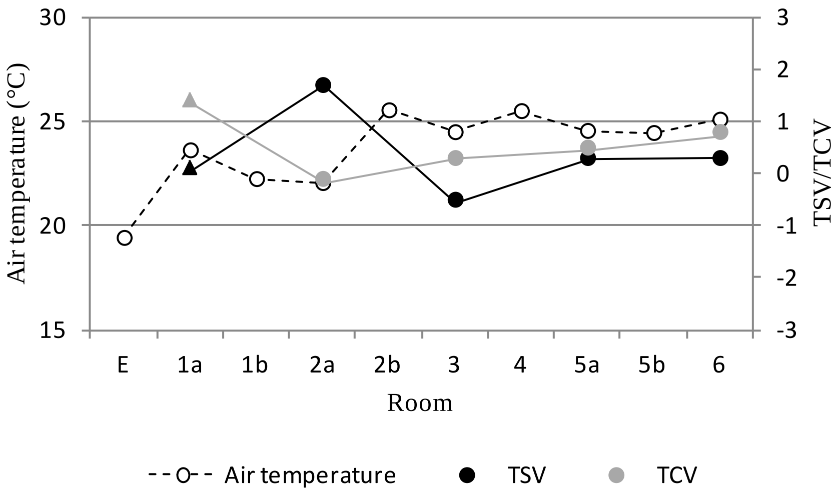


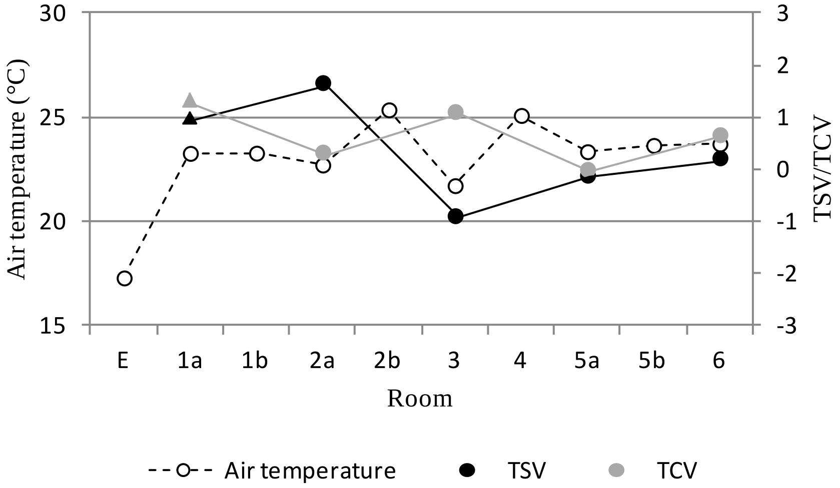
Participants' thermal sensation votes (TSV) reported immediately after the transition away from the neutrality versus the calculated PMV value for met =1.2 (white dots, dashed regression line) and met = 1.4 (black dots, continuous regression line) separately

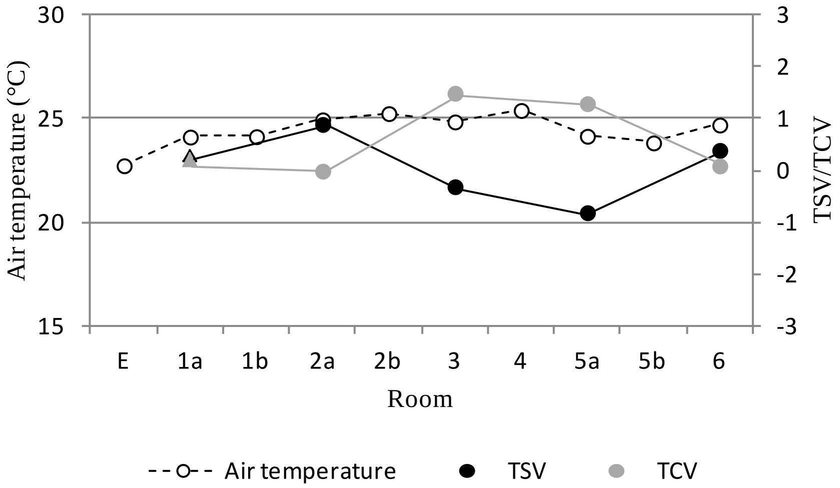
Appendix E

Field study in Kunsthistorisches Museum

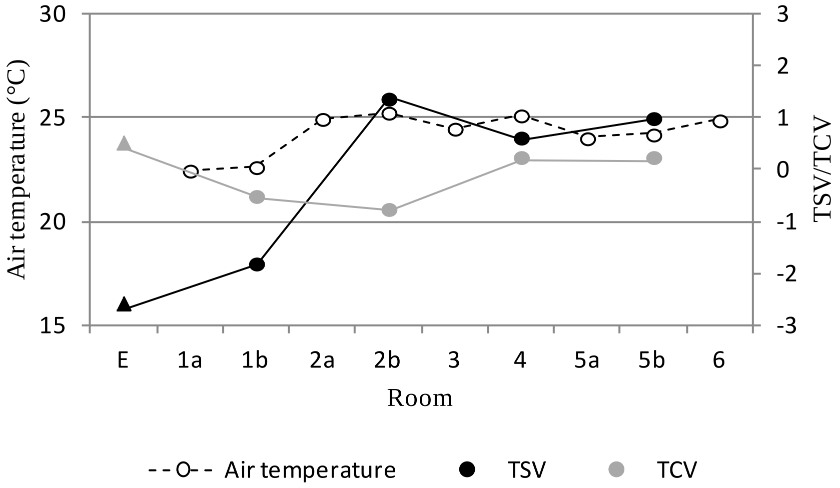


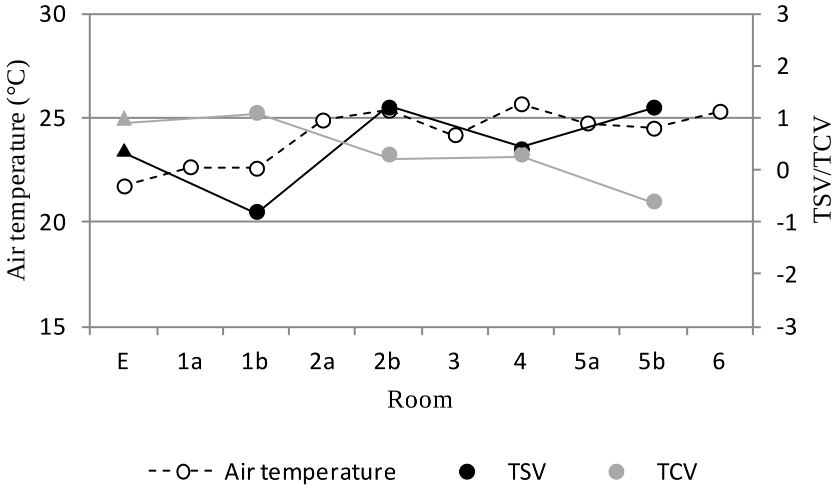


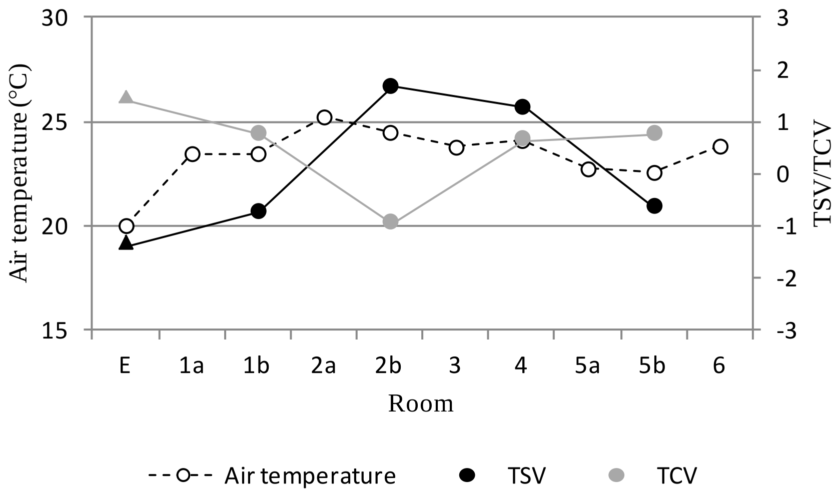


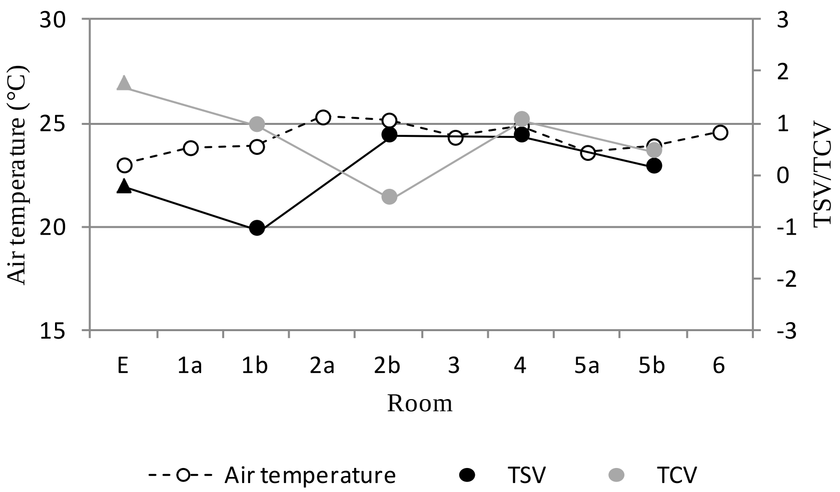


Temperature variation and subjective thermal sensation and comfort response immediately after a spatial transition phase of the route 1


30
25
20
15
Air temperature (°C)
3
2
1
0
-1
-2
-3
TSV/TCV
E
1a
1b
2a
2b
3
4
5a
5b
6
Room
Air temperature
TSV
TCV


30
25
20
15
Air temperature (°C)
3
2
1
0
-1
-2
-3
TSV/TCV
E
1a
1b
2a
2b
3
4
5a
5b
6
Room
Air temperature
TSV
TCV





Temperature variation and subjective thermal sensation and comfort response immediately after a spatial transition phase of the route 2

Curriculum vitae

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Education

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Publication

Wu Y, Mahdavi A. 2014. Assessment of thermal comfort under transitional conditions. Building and Environment, 76, 30-36

Wu Y, Mahdavi A. 2014. Subjective evaluation of thermal sensation and comfort subsequent to spatial transitions. Proceedings of the 13th International Conference on Indoor Air Quality and Climate, Hong Kong, July 7-12, 2014

Wu Y, Mahdavi A. 2013. Subject assessment of thermal transition in a museum: A case study. Proceedings of the 2nd ICAUD International Conference in Architecture and Urban Design Epoka University, Tirana, May 8-10, 2014

Wu Y, Orehounig K, Pont U, Schuss M, Mahdavi A. 2013. Assessing thermal comfort conditions in transitional states. Proceedings of the 2nd Central European Symposium on Building Physics, Vienna, September 9-11, 2013

Wu Y, Orehounig K, Pont U, Schuss M, Mahdavi A. 2013. Assessing thermal comfort conditions in transitional states. Proceedings of the 11th REHVA World

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