EVALUATION OF THERMAL COMFORT IN SEMI-OUTDOOR ENVIRONMENT

半屋外環境における熱的快適性評価に関する研究

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CHAPTER 1

GENERAL INTRODUCION

CHAPTER 1 GENERAL INTRODUCTION

1.1 OBJECTIVE OF RESEARCH

Remarkable progress in heating, ventilating, and air-conditioning (HVAC) engineering during the 20th century following W. H. Carrier's epoch making invention in 1902 has brought about a new philosophy into the environmental design, hitherto based on passive architectural approach. Primary design objective for indoor environments became the creation of a constant thermal environment at a given target value, defined in terms of air temperature, mean radiant temperature, humidity, and air velocity, independent of the outdoor climate and the configuration of the building.

On the other hand, atria or terraces designed to introduce natural outdoor elements such as sunlight and fresh air remain a popular technique in modern architecture to attract people from aesthetic aspects or to add diversity to the architectural environments. These moderately controlled semi-outdoor environments, often annexed to large-scale buildings such as hotels, offices, and shopping malls today, offer the occupants with the amenity of naturalness within an artificial environment, a temporal refuge from tightly controlled indoor working environment, and a thermal buffer to mitigate the large environmental step change during transition from indoor to outdoor.

Although HVAC engineering itself is a mature technology specialized in controlling indoor environment isolated from outdoor environment, the knowledge is limited on thermal comfort characteristics and environmental design strategies for semi-outdoor environments. The objective of this study is to evaluate the thermal comfort conditions of semi-outdoor environment from the two primary design requirements in modern architecture, passage space and short-term occupancy space.

1.2 DEFINITION OF SEMI-OUTDOOR ENVIRONMENT

Gehl (1987) indicated in his book *Life Between Buildings* the importance of environmental quality in outdoor public spaces to attract people and their social activities within, and thus to vitalize the entire community. Semi-outdoor environments lie in the same continuum, with a slight difference in the range of environmental control.

Thermal environment surrounding a man could be classified into several layers from an environmental engineering point of view according to the level of environmental control applied. The layers of thermal environment are described in Figure 1-1.

Outdoor environment is the outermost layer where no artificial adjustments are made. People would need to adjust themselves to the environment in order to achieve comfort. HVAC engineers have mainly dealt with the indoor environment enclosed within to provide desired thermal environment for occupants, and it is commonly further classified into occupied zone and personal / task zone to realize higher quality and efficiency of environmental control. As opposed to indoor environment subject to control at a given target value, moderately controlled environment located in between indoor and outdoor layers will be referred to as "semi-outdoor environment" in this study, and defined as "an architectural environment where natural outdoor elements are designedly introduced with the aid of environmental control". The level of control in semi-outdoor environment may range from

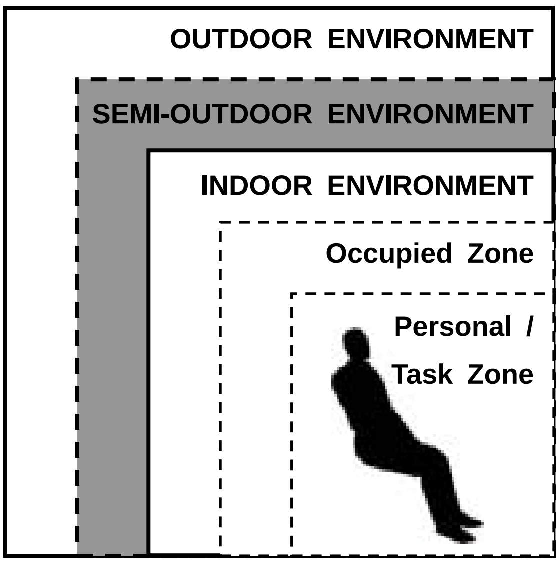


Figure 1-1. Layers of thermal environment surrounding a man

simple shading and wind shielding in an open structured terrace to mechanical heating, cooling, and ventilation in a closed glazing structure of an atrium. Of the numerous features for semi-outdoor environments, the scope of this study is focused on the typical application in modern architecture, large-scale urban precincts where visitors are allowed to pass through or stay at their will.

1.3 BACKGROUND

Thermal comfort design standards for semi-outdoor environment have not been organized except for the existing indoor thermal comfort standards for human occupancy such as ISO 7730 (1993) by International Organization for Standardization and ASHRAE Standard 55-92 (1992) by American Society of Heating, Refrigerating, Air conditioning Engineers. These standards do not specify the use of HVAC systems for environmental control, but narrow range of thermal comfort and constant nature of the thermal environment suggested by the standards are difficult to fulfill without the use of mechanical engineering. Instead, engineers have empirically derived environmental criteria for designing semi-outdoor spaces appropriate for the scope of their application (Mills, 1990) (SHASE, 2002). These practical criteria aimed for the design of atrium buildings have not been validated from the thermal comfort point of view. Further understanding of thermal comfort characteristics in the semi-outdoor environments would complement the design methods fostered by the practitioners.

Thermal comfort indices such as Predicted Mean Vote (PMV) (Fanger, 1970) and New Effective Temperature (ET*) (Gagge et al., 1971) underlying the current thermal comfort standards were developed from the principle of heat exchange between man and the thermal environment, associated with the results of subjective sensation votes. Votes were collected from subjective experiments conducted in climate chambers where subjects were exposed to a given combination of air temperature, mean radiant temperature, air velocity, humidity, clothing, and metabolic rate for several hours. These methods and results may apply to air-conditioned indoor environment such as offices or theaters due to the similarity in occupancy conditions. However, numerous differences exist in occupancy conditions of semi-outdoor environment. In many cases, occupants are not required to stay in semi-outdoor environments for hours, and the main use would be a passage or an agora where people are free to stay or leave at their will. Thermal comfort conditions should be investigated with regard to how the semi-outdoor architectural environments are actually used, from the viewpoint of transition phase while walking through and the short-term occupancy phase for a period of less than an hour.

While passing through different spaces, people experience continuous environmental step changes in a short amount of time. The heat exchange between man and the environment would not reach steady state during that period, and transient thermal conditions should be considered for evaluation of transition phase through semi-outdoor environments. Thermal comfort within the semi-outdoor environment during transition would be less of a concern due to the short occupancy time, but the influence on thermal comfort in the succeeding environment should be investigated to evaluate the effects of semi-outdoor environment as the thermal buffer.

Thermal adaptation of the occupants is another factor that should be taken into account, since occupants would not be able to achieve comfort as passive recipients of thermal environment in semi-outdoor environments. Apart from subjective experiments where subject are limited with their free choices, numerous field studies have shown that people take actions to adapt themselves to the thermal environment when an environmental change occurs to produce discomfort (Nicol and Humphreys, 1973). Thus, higher degree of flexibility in behavioral adaptation has the effect of improving comfort (Humphreys and Nicol, 1998). Psychological adaptation is another form of adaptation, which refers to an altered perception of, or response to, the thermal environment resulting from one's thermal experiences and expectations (Brager and de Dear, 1998). An office field study showed that higher level of satisfaction is achieved when an occupant perceived to have more control over his thermal environment (Williams, 1995). In naturally ventilated buildings where indoor thermal conditions are recognized to be variable, but where occupants have greater flexibility in adaptation, occupants were found to have broader comfort range than those in fully air-conditioned buildings (de Dear and Brager, 1998). Although little study has been conducted in semi-outdoor environments, it is likely that people seek environments differing from indoor when given the settings closer to outdoor. These circumstances may contribute to evoke behavioral and psychological adaptation to compensate for the deviation of environment from thermal neutrality predicted by thermal comfort indices. As climate chambers are unable to simulate the settings analogous to semi-outdoor environment, an investigation on thermal comfort conditions with regard to adaptation needs to be conducted under real circumstances.

1.4 LITERATURE REVIEW OF RELATED RESEARCH

1.4.1 Existing Thermal Comfort Standards and Their Basis

In ASHRAE Standard 55-92, thermal comfort is defined as "the condition of mind that expresses satisfaction with the thermal environment". The thermal comfort conditions are defined in both ASHRAE 55-92 and annex of ISO 7730, and recommend less than 10 % of the occupants dissatisfied within a space as one of the guidelines. The optimum operative temperature and 90 % acceptability range are given in Table 1-1. ISO 7730 does not prescribe the actual operative temperature range, but the values were calculated from the same input variable as ASHRAE 55-92 i.e. light, primarily secondary activity (< 1.2 met) at 50 % relative humidity and mean air speed < 0.15 m/s.

Table 1-1. Optimum operative temperature and 90 % acceptability range

	Season	Icl (clo)	Optimum operative temperature (°C)	Operative temperature range (°C)
ASHRAE 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

Both standards yield a similar optimum operative temperature range, but the upper range of ASHRAE 55-92 for 90 % acceptability operative temperature range is slightly lower, due to the difference in the thermal comfort index on which the standard is based. The standards are based on comfort models, ET* and PMV for ASHRAE and ISO respectively, that predict subjective thermal state as a result of steady-state heat balance between man and the environment, mediated by autonomic physiological responses. Parameters required to calculate the indices are air temperature, mean radiant temperature, humidity, air velocity, clothing, and metabolic rate. A brief review of the two indices will be given in the following section.

1.4.1.1 The New Effective Temperature (ET*) and Standard New Effective Temperature (SET*)

Houghton and Yaglou (1923) developed the original Effective Temperature (ET), one of the earliest thermal comfort indices, as a part of the American Society for Heating and Ventilating Engineers (ASHVE) projects for defining the thermal comfort conditions in air-conditioned spaces. Subjects entered back and forth the two climate chambers controlled at different sets of air temperature and humidity, and found the combination of air temperature and humidity that produced the equal thermal sensation. Although this empirically based index was adopted by many authorities and widely used by HVAC engineers for nearly 50 years, it was recognized to overestimate the effect of humidity at low temperatures and underestimate the effect at high temperatures. In 1971, Gagge et al. (1971) proposed the new effective temperature ET* based on the physics of heat transfer and physiology of thermoregulation. Two-node model of human thermoregulation consisting of a core layer and a shell layer was utilized to simulate the mean skin temperature and skin wettedness of a man in a given environment. Skin wettedness underlying this index is the ratio of the actual evaporative heat loss at the skin surface to the maximum loss, and is found to be an excellent predictor of warm discomfort. ET* indicates the value which produces the same thermal sensation for different sets of temperature and humidity, provided that air velocity, clothing, and activity were the same. The index was incorporated into ASHRAE 55 in 1974 in its restricted form of sedentary activities, and the 90 % acceptability range in the standard is based on this index. The standard new effective temperature (SET*) was proposed later in 1986, which was defined as the equivalent temperature of an isothermal environment at 50 %rh in which a subject, while wearing clothing standardized for the activity concerned, has the same heat stress and thermoregulatory strain as in the actual environment. The effect of humidity, especially in its high regions, has been the main scopes of the three effective temperatures due to the cooling requirements in hot and humid areas within the United States.

1.4.1.2 Predicted Mean Vote (PMV)

Fanger (1970) introduced the comfort equation, a heat balance equation between the generated heat within human body and the actual heat loss to the surrounding environment, as one of the requirements for thermal neutrality.

$$M - W = C + R + E + K + RES \qquad (1\text{-}1)$$

where

- M: Metabolic rate [W/m^2]
- W: External work [W/m^2]
- C: Heat loss by convection [W/m^2]
- R: Heat loss by radiation [W/m^2]
- E: Heat loss by evaporation [W/m^2]
- K: Heat loss by conduction [W/m^2]
- RES: Heat loss by respiration [W/m^2]

If the equation is not satisfied, the man is in either warm or cool thermal discomfort according to the excess or deficit of the heat balance. The residual of the comfort equation, termed the thermal load, is related to the degree of thermal sensation away from thermal neutrality, and a thermal sensation index, PMV, was formulated. PMV is defined as the predicted mean value of the vote by a large group of persons if exposed to the actual environment to be expressed on the following seven-point ASHRAE psychophysical scale:

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

PMV itself is unable to predict the degree of occupant satisfaction in a given thermal environment. Predicted Percentage of Dissatisfied (PPD), the percentage of a group of occupants predicted to be dissatisfied with the thermal environment, was proposed in relation to PMV, standing on an assumption that a person who voted ±2 or greater was dissatisfied. PMV and PPD became the standardized method to evaluate thermal comfort as ISO 7730 in 1984. PMV is found to yield good results around sedentary comfort condition, but less accurate when the metabolic rate is high, clothing is heavy, or environmental conditions are away from comfort.

The term “TSV” which is the abbreviation for “(whole body) thermal sensation vote” is used in Chapter 3 of this thesis. While PMV refers to the theoretically derived index, TSV refers to the mean thermal sensation vote of actual subjects made during a particular experiment. Although the two terms are easily confounded, the conceptual difference needs to be recognized for interpretation of the results.

1.4.2 Empirically Derived Design Criteria for Atrium Buildings

Semi-outdoor environment often appears in the form of an atrium building in modern architecture. Atrium in modern architecture gained its fame in the 1960's when architect John Portman designed a series of large-scale atrium hotels in the United States. The number of newly built atria with various design concepts grew rapidly from the 1970's, and it still is a popular design strategy today.

Design concept of an atrium from environmental engineering point of view varies dramatically depending on the climate of the building location and the comfort level aimed for inside. Climate has a large influence on the amount of cooling or heating load of an atrium, and the basic structure is chosen by the orientation of environmental control: heating, cooling, or both. The comfort level is largely divided into four categories of "canopy", "buffer", "tempered buffer" and "full comfort" (Saxon, 1983). Very few literature provide the actual target value for these specifications, but two empirically derived design criteria, one from UK and the other from Japan, are given in Tables 1-2 and 1-3 respectively. The characteristic difference between the two criteria is that the former is winter oriented and the latter is summer oriented. Although the winter climate is similar in both countries, Japan has a hot and humid summer compared to moderate summer in the UK. Summer target temperatures are generally lower in Japan due to the difference in humidity. Winter target temperature is also higher in Japan, suggesting that higher comfort level is generally required for an atrium in Japan.

Twenty percent of atrium buildings in Japan are office buildings. Integrated facilities follow with 16 %, and hotels and public facilities with 13 % respectively. The main use of atrium is entrance hall, 40 %, and agora, 24 % (Yoshino et al., 1996). Most of atria are expected to fall in between the categories of "tempered buffer" and "partial comfort", where indoor air temperature would range from 18 to 28 °C throughout the year. Although many studies have dealt with heat load calculation and detailed thermal environment prediction techniques for thermal system design of atria to accomplish these values (Kato et al., 1995), actual comfort conditions resulting from the particularly controlled environment have not been investigated in large numbers.

Table 1-2. Environmental criteria for UK atrium (Mills, 1990)

Atrium Type	Performance Level	Applications	Comfort Criteria	
			Heating (Winter)	Cooling (Summer)
Canopy	Shelter, shade. No air containment.	Shopping precincts. Links between buildings, or alongside buildings.	Ambient air tempperature. No heating.	Ambient air temperature. No cooling.
Buffer	Winter air containment. Shelter, shade, summer natural ventilation	Conservatory link. Covered courtyard. Covered shopping center.	No heating. Air temperature above ambient due to internal solar gains by 5°C+	No cooling. Natural ventilation used to remove excess heat. Peak air temperature around 30 to 35 °C
Tempered Buffer	Winter air containment. Shelter, shade, background heating. Summer natural ventilation	Office entrance halls. Enclosed shopping centers.	Air temperature heated to 10 °C in occupancy zone.	As above.
Partial Comfort	Winter air containment. Shelter, shade, heating. Summer natural and/or mechanical ventilation.	Office entrances and meeting halls. Enclosed shopping centers. Hotels. Restaurants, hospital. Glazed links.	Air temperature heated to 19 °C in occupancy zone. Radinat heating to offset cold glazing.	As above.
Full Comfort	Winter air containment. Shelter, shade, heating ventilation and mechanical cooling	Office space, banking halls. Enclosed shopping centers. Prestige hotels, restaurants.	Winter design 19 °C minimum.	Summer design 25 °C maximum. Mechanical cooling.
Passive Solar	Can be between buffer and full comfort according to design approach.	Any. Design approach seeks to optimize solar gains during winter and maximize natural ventilation effects in summer.	Winter design up to 19 °C as designed. Heating to supplement solar gains.	No mechanical cooling. Thermal stack effects optimized to achieve high air changes Peak temperatures around 27 to 30 °C.

Table 1-3. Environmental criteria for Japanese atrium (SHASE, 2002) (modified by Nakano, 2002)

Atrium type*	Performance level	Application		Thermal environment			
				Summer		Winter	
				Operative temp.	Humidity	Operative temp.	Humidity
Canopy - Buffer	Openness of oudoor setting required. Avoid rain for activity within.	Recreation ground		May range form outdoor level to indoor level due to concept.			
Tempered buffer	No requirements. Semi-outdoor environment for pleasure.	Passage		28°C-outdoor	Drift	18°C approx.	Drift
				No severe requirements.			
Tempered buffer	Openness and oudoor setting required.	Agora		28°C-outdoor	Drift	18°C approx.	Drift
				No severe requirements.			
Partial comfort - Full comfort	Considered as part of indoor space.	Entrance		26-28°C	Drift	18-22°C	Drift
				Intermediate environment between indoor and outdoor.			
Full comfort	Sofas and tables installed for long term occupancy.	Lobby, meeting space		26°C approx.	Drift	22°C approx.	Drift
Full comfort	Normal indoor comfort condition.	Exhibition space		26°C	Drift	22°C	Drift
Full comfort	Normal indoor comfort condition.	Shops	Merchandise	26°C	Drift	22°C	Drift
Full comfort	Normal indoor comfort condition.	Shops	Café, restautrant	24-26°C	Drift	22°C	Drift

*Modification made by author

1.4.3 The Adaptive Model

Field survey is an alternative approach to study thermal comfort besides subjective experiment on which the current thermal comfort standards are based. Although subjective experiments have the merit of controlling intended variables, care must be taken to interpret the results for practical use because of the artificial settings created for the experiment. Various researchers have conducted field surveys at homes, offices, schools, etc. to compare the results with the prediction of thermal comfort indices. Nicol and Humphreys (1973) pointed out that mean thermal sensation votes of indoor occupants collected from various field studies showed a poor correlation with the mean indoor temperatures. Based on the observations on clothing adjustments and environmental adjustments by operable windows, they have concluded that occupants were adapting to the given thermal environment to produce comfort, and that thermal comfort was a part of a self-regulating system. This philosophy, named the Adaptive Model, is contrary to the heat balance equation based thermal comfort indices where a man is considered to be a passive recipient of a given thermal environment.

Adaptation can be divided into three categories: behavioral adaptation, physiological adaptation and psychological adaptation (Brager and de Dear, 1998). Behavioral adaptation includes all actions to retain comfort, such as clothing adjustment, metabolic rate adjustment, turning on a fan, opening windows, finding a better location to stay, etc. Behavioral adjustments offer the greatest opportunity to maintain body heat balance. Physiological adaptation may range from fairly short-term seasonal acclimatization to genetic heritage lasting for several generations. However, the neutral temperature derived for Danish (Fanger, 1970), Singaporean (de Dear et al., 1991) and Japanese (Tanabe and Kimura, 1994) subjects yielded insignificant differences, suggesting that the effect of physiological adaptation is small near thermally neutral conditions. Psychological adaptation refers to the adjustment in perception of a given condition. Situation deviating from one’s expectations would evoke discomfort, but when a person becomes accustomed to a given situation, he would gradually relax his expectation and know what to expect. Although little work is documented for the psychological adaptation process in thermal comfort, it is thought to play a significant role in explaining the differences in observed and predicted thermal sensation.

The Adaptive Model does not maintain that any thermal condition would become acceptable for all occupants at all times. Circumstances such as climate, affluence, culture and social contexts restrict certain adaptive actions, and thus restrain the “adaptive opportunity” (Humphreys and Nicol, 1998). Greater freedom in adaptation would enhance comfort, but restrained adaptation would lead to further discomfort. It could also be said that imposed variation produces discomfort, while chosen variation is likely to reduce discomfort.

De Dear and Brager (1998) assembled a large database of office field survey around the world, comprised of over 20,000 observations of subjective votes and corresponding sets of environmental variables, to conduct statistical test between the thermal comfort conditions of naturally ventilated buildings and air-conditioned buildings. Although the degree of variation was greater for occupants of naturally ventilated buildings, behavioral adaptation in terms of clothing and air movement adjustments was observed as a function of indoor operative temperature in both types of buildings. Indoor comfort temperature was found to correlate well with prevailing outdoor temperature. By taking the behavioral adaptation into account, comfort temperature predicted by PMV matched the observed comfort temperatures in air-conditioned buildings, while large discrepancies were found for naturally ventilated buildings. These results suggest that comfort conditions in naturally ventilated buildings, which has a broader adaptive opportunity than air conditioned buildings, could not be predicted by the heat balance equation. Behavioral adaptation was taken into account. Thermal environment in the measured buildings are too moderate to give rise to physiological adaptation. The process of elimination gave psychological adaptation the rationale to explain the discrepancy between predicted and observed comfort temperature in naturally ventilated buildings. It was concluded that thermal comfort is achieved by correctly matching indoor thermal conditions and expectations based on past experiences and architectural norms. The Adaptive Model is being incorporated in to the revision to ASHRAE Standard 55 as “optional method for determining acceptable thermal conditions in naturally conditioned spaces”, and is currently undergoing the public review process (de Dear and Brager, 2001).

The role of adaptation on thermal comfort is depicted in Figure 1-2 (de Dear, 2002). The most important implication of the Adaptive Model is that factors beyond fundamental physics and physiology affect perception of thermal environment and condition for comfort.

Thermal sensations, satisfactions, and acceptability are all influenced by the match between one's expectation about the thermal conditions in a particular context, and what really exists. Common findings on adaptation by the various researchers identify that outdoor climate, not immediate indoor climate, has large influence on behavioral and psychological adaptation.

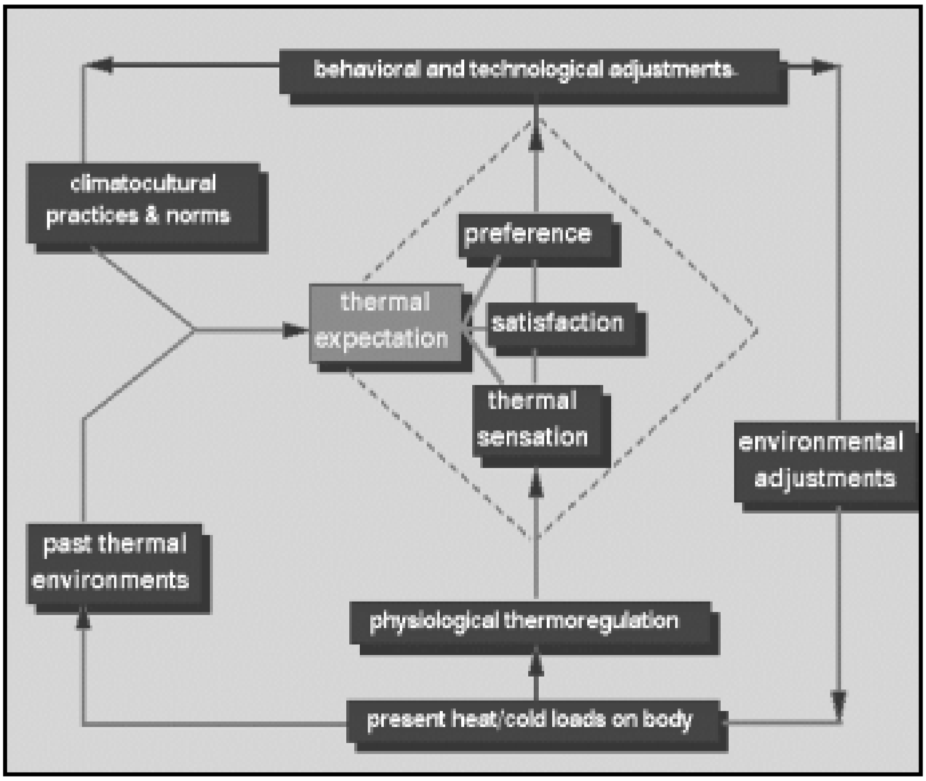


Figure 1-2. Role of adaptation on thermal comfort by de Dear (2002)

1.4.4 Thermal Comfort During Environmental Step Changes

Semi-outdoor environment acts as a thermal buffer space between indoor and outdoor for occupants walking in and out of the building to mitigate the sudden change in thermal environment. Transition process through a buffer space such as entrance halls and atria may be regarded as a series of environmental step changes through indoor, buffer space and outdoors. Although a standard evaluation method for transient thermal comfort has not been defined in the literature, numerous subjective experiments have been conducted from as early as 1960's to indicate the characteristic difference between steady state and transient thermal comfort.

Gagge et al. (1967) conducted a series of subjective experiments where subjects moved from comfortable thermal condition (28 or 29 °C) to hot (48 °C) or cold (17.5 °C) environments and back. He reported that thermal sensation and comfort sensation could be explained with physiological variables such as mean skin temperature and sweating conditions when moving from comfortable to uncomfortable thermal environments, but sensations quickly reached the steady state neutral values leading the physiological conditions in the adverse transition, describing the latter phenomenon as "anticipatory". Rohles et al. (1977) have conducted a similar experiment, 23.2 °C neutral condition +9 °C and –7.6 °C, to investigate the "supermarket experience" which refers to the feeling of coldness that customers experience when they go into an air-conditioned store during the summer. He also concluded that thermal and comfort sensations quickly reached the steady state when entering the comfortable environment, and thermal comfort was not affected by previous uncomfortable environment the subjects experienced. The occupancy period for each environment exceeded more than an hour for the above experiments, and it would be difficult to apply these results directly to the situation in semi-outdoor environment.

Knudsen et al. (1990) reported the results on relatively shorter transitions. Subjects stayed in a standard comfortable environment for an hour and moved through an environment of +2 °C and –2 °C every 30 minutes for a total of 4 transitions. Thermal sensation votes immediately reached the steady state values after step-up changes, but an overshoot of thermal sensation was observed upon experiencing step-down changes, suggesting that humans were more sensitive to lower temperature changes.

Kuno et al. (1987) indicated the presence of 2 different types of comfort, negative comfort and positive comfort (pleasantness). Negative comfort describes the state of no thermal strain during steady-state condition, and positive comfort describes the state mind accompanying the dismissal of thermal strain during transient conditions. A step change transition from uncomfortable to comfortable environment is expected to result in positive comfort, and this may needed to be considered when evaluating the semi-outdoor environment during transition phase.

1.4.5 Mobile Measurement Apparatus for Thermal Environment

Measurement of thermal environment is critical for assessment of thermal comfort. As it is unrealistic to measure every point on the coordinate of an environment in interest, representative points must be chosen to fit the objective of the measurement. Thermal environment in the actual architectural environments is complex compared to uniform and constant conditions in climate chambers. Windows introduce solar radiation and draft into the perimeter zone, and furniture or heat generating equipments form an intricate indoor landscape to create heterogeneous indoor thermal environment. Air temperature and humidity are comparatively uniform in semi-outdoor environments, but radiation and air velocity differ dramatically depending on the shade or wind obstruction around the measurement location. Inappropriate selection of representative points or systematic errors in measurement devices would lead to illogical evaluation. On the other hand, circumstances such as time, cost, and personnel often restrict large-scale measurement plans, enabling only a limited number of items and measurement points. A practical measurement apparatus is required to carry out effective evaluation of thermal environment. The scope of measurement will be focused on immediate thermal environment around a walking or a seated man to assess thermal comfort in semi-outdoor and indoor environments.

1.4.5.1 Standards for Measurement of Thermal Environment

ISO 7726 (1998) and ASHRAE 55-92 (1992) specify the protocols for determining the combination of environmental parameters (air temperature, mean radiant temperature, humidity and air velocity) in the built environment, including the necessary specifications for measurement devices and measurement heights. Compliance with these protocols would ensure accuracy comparable to laboratory measurements and thus allows for the rational comparison between thermal comfort indices derived from subjective experiments and occupant responses in the field.

The specifications for the measurement devices are given in Table 1-4 for both standards. ISO 7726 gives a more detailed prescription according to two environmental classifications, Class C for thermal comfort and Class S for heat stress. Desired values for Class C are analogous to that of ASHRAE 55-92, and evaluation of thermal comfort in indoor environments designed for occupancy would require fulfillment of these values. Additional care is needed for evaluation of radiation and air velocity in semi-outdoor environments due to a wider range of environmental variables.

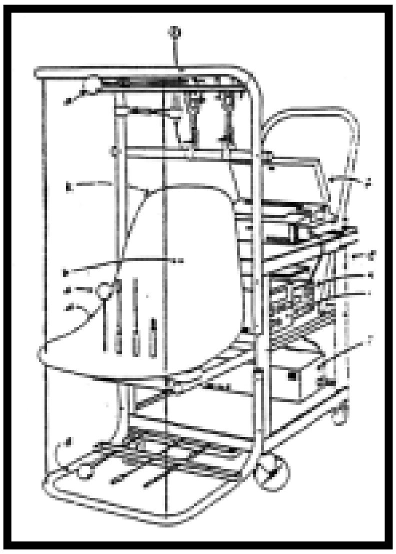
Four measurement heights around a man are specified to assess local thermal discomfort resulting from vertical temperature difference or draught. The ankle level is defined as 0.1 m above floor level, abdomen of a seated person as 0.6 m, head level of a seated man or abdomen level of a standing man as 1.1 m, and head level of standing man as 1.7 m. Thermal environment defined at these heights can be regarded as representative environment of a seated and standing man.

Table 1-4. Specifications for thermal environment measurement devices

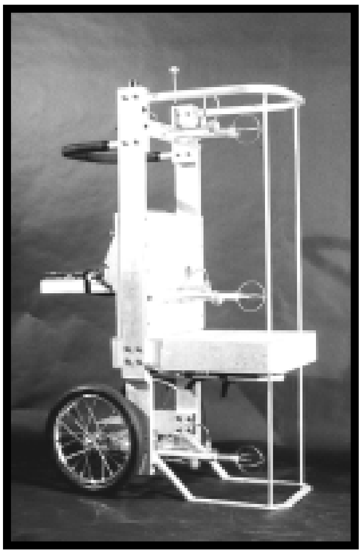
	Quantity	Symbol	Measuring range	Accuracy: Required	Accuracy: Desired	Response time (90%)
ASHRAE 55-92	Air temperature		5 to 40 ℃	± 0.2 ℃		Appropriate for application
	Mean radiant temperature		5 to 40 ℃	± 0.2 ℃ (Desired)		Measurement within 10 min.
	Radiant temperature asymmetry		0 to 20 ℃	± 1 ℃		1 min. or less
	Air velocity		0.05 to 0.5 m/s	± 0.05 m/s		1 to 10 sec. 0.2 sec.desirable
	Dew-point temperature		1 to 26 ℃	± 0.5 ℃		Measurement within 10 min.
	Surface temperature		0 to 50 ℃	± 0.5 ℃		Appropriate for application
ISO 7726: Class C (Comfort)	Air temperature	t_a	10 to 40 ℃	± 0.5 ℃	± 0.2 ℃	Shortest possible
	Mean radiant temperature	t_r	10 to 40 ℃	± 2 ℃	± 0.2 ℃	Shortest possible
	Plane radiant temperature	t_{pr}	0 to 50 ℃	± 0.5 ℃	± 0.2 ℃	Shortest possible
	Air velocity	v_a	0.05 to 1 m/s	± | 0.05 + 0.05 v_a | m/s	± | 0.02 + 0.07 v_a | m/s	Required: ± 0.5 s Desired: ± 0.2 s
	Partial vapor pressure	Pa	0.5 to 3.0 kPa	± 0.15 kPa		Shortest possible
	Surface temperature	t_s	0 to 50 ℃	± 1 ℃	± 0.5 ℃	Shortest possible
ISO 7726: Class S (Thermal stress)	Air temperature	t_a	-40 to +120 ℃	-40 to 0 ℃ ± (0.5 + 0.01 |t_a|)℃ > 0 to 50 ℃ ± 0.5 ℃ >50 to 120 ℃ ± [0.5 +0.04 (t_a-50)] ℃	(required accuracy) / 2	Shortest possible
	Mean radiant temperature	t_r	-40 to +150 ℃	-40 to 0 ℃ ± (5 + 0.02 |t_r|)℃ > 0 to 50 ℃ ± 5 ℃ >50 to 150 ℃ ± [5 +0.08 (t_r-50)] ℃	-40 to 0 ℃ ± (0.5 + 0.01 |t_r|)℃ > 0 to 50 ℃ ± 1 ℃ >50 to 150 ℃ ± [0.5 +0.04 (t_r-50)] ℃	Shortest possible
	Plane radiant temperature	t_{pr}	0 to +200 ℃	-60 to 0 ℃ ± (1 + 0.1 |t_{pr}|)℃ > 0 to 50 ℃ ± 1 ℃ >50 to 200 ℃ ± [1 +0.1 (t_{pr}-50)] ℃	(required accuracy) / 2	Shortest possible
	Air velocity	v_a	0.2 to 20 m/s	± | 0.1 + 0.05 v_a | m/s	± | 0.05 + 0.05 v_a | m/s	Shortest possible
	Partial vapor pressure	Pa	0.5 to 6.0 kPa	± 0.15 kPa		Shortest possible
	Surface temperature	t_s	-40 to +120 ℃	<-10 ℃ ± [1 + 0.05 (-t_s-10)] ℃ -10 to 50 ℃ ± 1 ℃ > 50 ℃ ± [1 + 0.05 (t_s-50)] ℃	(required accuracy) / 2	Shortest possible

1.4.5.2 Mobile Measurement Apparatus

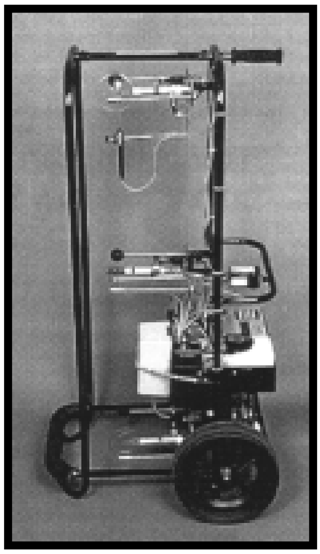
Benton et al. (1990) developed a mobile measurement cart for thermal comfort field survey in offices. The cart was equipped with air temperature, globe temperature, air velocity, and humidity sensors at 0.1, 0.6, and 1.1 m above floor level. A chair was attached in front to simulate the configuration of a chair for a seated person. All the devices were powered with batteries to enable smooth cordless relocation from one workstation to another. The cart was placed in the seat position of an office worker at desk to measure the thermal environment for 5 minutes, while the occupant answered the thermal comfort questionnaire. By this procedure, the cart was able to record the immediate thermal environment of a questionnaire respondent, which was then used to calculate thermal comfort indices for comparison with actual sensation votes. Early thermal comfort field studies had been criticized for crudeness of thermal environment measurement, but this survey protocol realized the laboratory grade measurement in the field. The use of mobile measurement cart became a popular technique in office surveys, and various types of carts have been built for the purpose (U.C.Berkley, 1991) (Cena and de Dear, 1999). The use of mobile measurement apparatus in urban outdoor environments have also been reported in several studies. Matzarakis et al. (1999) used a small handcart equipped with revolving pyranometer and pyrgeometer for radiation measurement to assess heat stress in the urban environment. Hoyano et al. (1998) developed a portable cylinder type apparatus for a surveyor to carry around throughout the day to examine the thermal environment an urban resident would experience during everyday life. Fast-response globe thermometer and pyranometer were used for estimation of radiant environment. Similar investigation was conducted by Song et al. (2001) using a cart with ability to measure thermal variables at 4 heights defined in ISO and ASHRAE standards. Measurement of radiation was conducted by globe thermometer, ellipsoid operative temperature sensor, and pyranometer. Measurement protocols for the latter two apparatuses were aimed for measurement of continuous thermal environment, while others were designed for quasi-steady state assessment in discrete measurement points. Pictures and drawings of the above apparatuses are presented in Figure 1-3Very few of these mobile apparatuses had considered the evaluation of thermal comfort in both indoor and semi-outdoor environments, covering a wide range of environmental variables and measurement points.



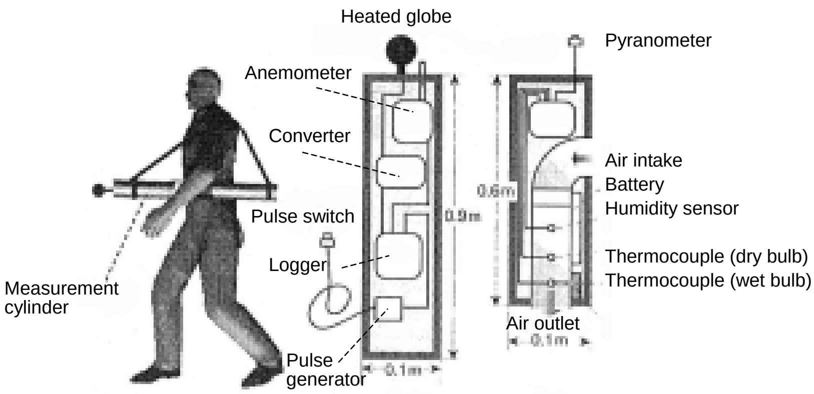
(Benton et al., 1990)



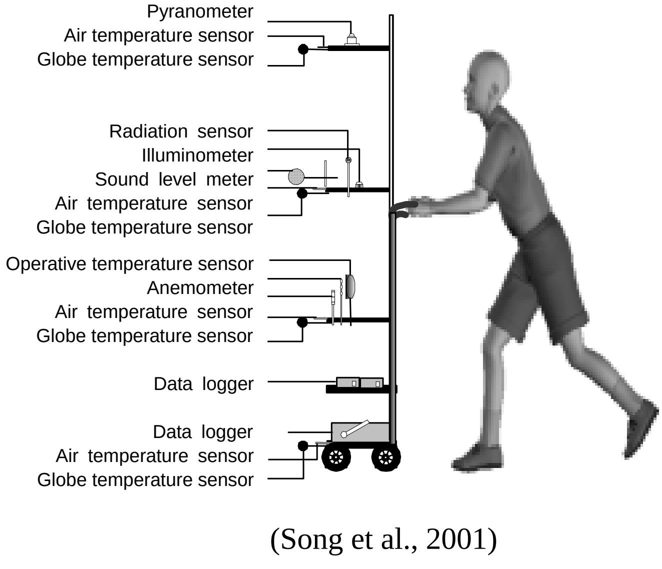
(U.C.Berkeley, 1991)



(Cena et al., 2001)



(Hoyano et al., 1990)



(Song et al., 2001)

Figure 1-3. Mobile measurement apparatuses for thermal environment

1.5 OUTLINE OF RESEARCH

Thermal comfort characteristics and thermal comfort conditions in large-scale urban semi-outdoor environments were investigated from the two primary design requirements in modern architecture, passage space and short-term occupancy space. Assessment of passage phase was conducted by regarding the transition process through semi-outdoor environment as successive environmental step changes. Environments were considered to be steady state, and transient evaluation was focused on physiological and psychological characteristics of a person walking through. Numerical simulation of human thermoregulation, subjective experiments, and field surveys were utilized for the purpose. Adaptation of occupants was taken into account for short-term occupancy evaluation. The thermal environments were regarded as quasi-steady state, and psychological and physiological adaptation in relation to thermal environment were observed through field surveys.

In Chapter 1, the purpose of this study and the definition of “semi-outdoor environment” are described. Background of the research and the literature review on related researches are also presented.

In Chapter 2, transient thermal comfort of a passer-by was investigated for passage phase of semi-outdoor environment using numerical simulation of human physiology. The structure of the thermoregulation model, 65MN, is presented in the first section. A mobile measurement cart was developed to conduct seasonal field measurements in the actual semi-outdoor environment. The measured environmental data were used as boundary conditions for physiological simulation of an imaginary visitor.

In Chapter 3, the influence of environmental condition on transient thermal comfort was investigated for semi-outdoor environment acting as a buffer space from indoor to outdoor. Subjective experiments were conducted to examine how transient thermal comfort succeeding a short walk was affected by the environmental condition of the buffer space. A total of 120 subjects participated in the experiment conducted in a climate chamber controlled to simulate indoor, buffer, and outdoor environments. Transient characteristics were examined physiologically and psychologically.

In Chapter 4, the results of seasonal field surveys conducted in an office environment with multi-national workers are described. The influence of limited adaptation on thermal comfort condition in indoor environment was examined from physical measurements and 406 questionnaire responses on thermal comfort.

In Chapter 5, a series of seasonal field surveys conducted in 4 semi-outdoor architectural environments to evaluate the thermal comfort characteristics for short-term occupancy is described. Investigation of occupancy condition, measurement of thermal environment, and questionnaire survey were integrated into the survey design, yielding 2248 sets of data for analysis.

In Chapter 6, the findings from each chapter are summarized.

The flow of the present thesis is summarized in Figure 1-4.

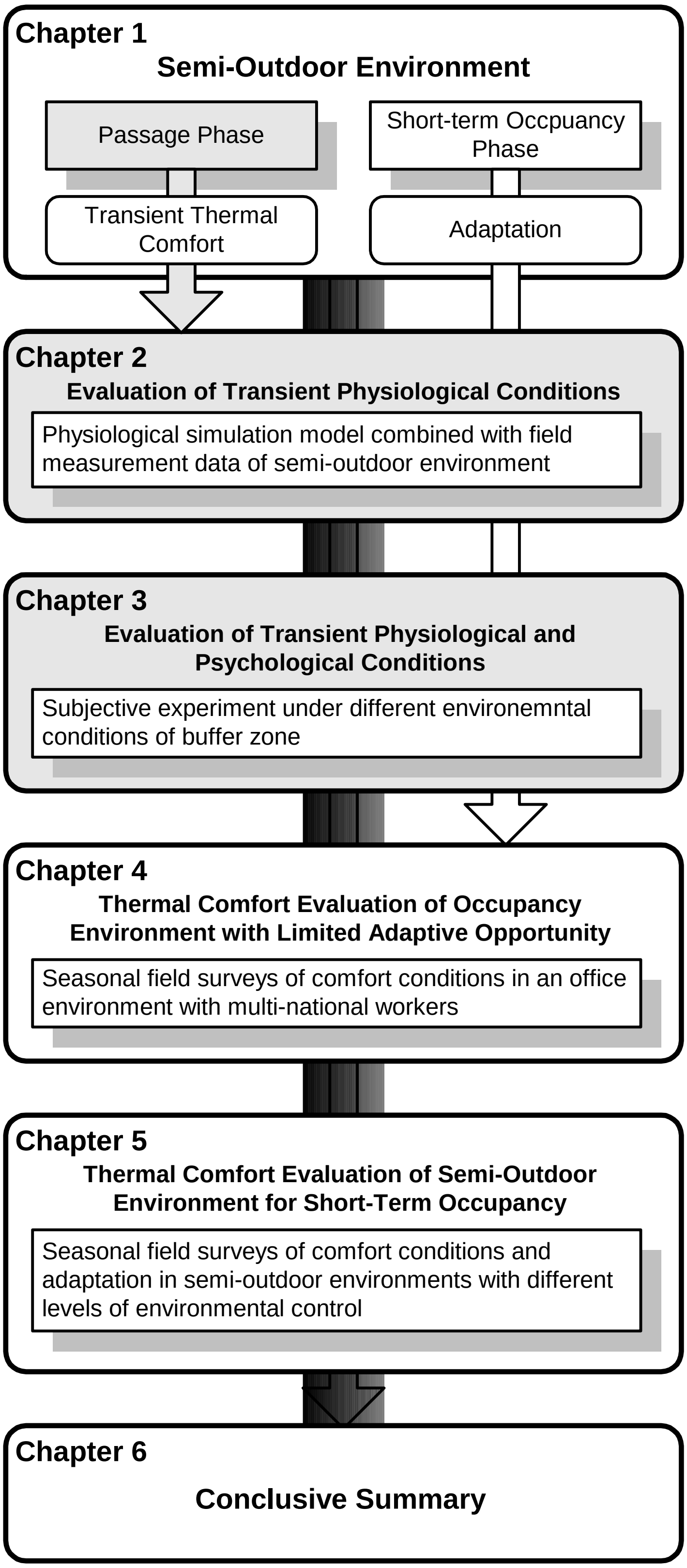


Figure 1-4. Research flow

CHAPTER 2

EVALUATION OF TRANSIENT THERMAL COMFORT USING NUMERICAL THERMOREGULATION MODEL (65MN)

CHAPTER 2 EVALUATION OF TRANSIENT THERMAL COMFORT USING NUMERICAL THERMOREGULATION MODEL (65MN)

2.1 INTRODUCTION

Low energy consumption of the buildings is one of the key issues in sustainable development in the field of architecture. It is not always necessary to keep constant optimal temperature by HVAC system especially in the buffer zones between indoor and outdoor. These buffer zones are usually discussed from aesthetic point of view, but Hayashi et al. (1996) have reported that a large atrium located at the entrance of the office building functioned to mitigate the heat stress of a person upon entering or leaving the building. Evaluation of transient spaces should not be performed only by conventional indoor environment evaluation schemes applied to individual spaces, but also by considering the sequential space composition. It is considered necessary, therefore, to make a seasonal evaluation of the thermal environment in transient spaces from indoor to outdoor and from outdoor to indoor. A combination of field surveys using a mobile instrumental cart and a numerical simulation by human thermoregulation model was proposed for this purpose.

2.2 65-NODE THEMOREGULATION MODEL

The 65 Multi-Node Thermoregulation Model, 65MN, is a mathematical model of human thermoregulation based on the Stolwijk model (Stolwijk, 1971). 65MN represents the anthropometric data of an averaged man with the body weight of 74.430kg and the body surface area of 1.870m^2. The whole body is divided into 16 body segments (head, chest, back, pelvis, left shoulder, right shoulder, left arm, right arm, left hand, right hand, left thigh, right thigh, left leg, right leg, left foot, and right foot) corresponding to the thermal manikin, Anne (Tanabe et al, 1994). The subscript "*i"(1-16)* represents the segment number in the following equations. Individual body segment consists of core, muscle, fat and skin layers. This layer division is expressed with the subscript "*j"(1-4)*. The layers add up to a total of 64, and each layer is represented by a node. In addition, the central blood compartment represents the 65th node, and 65MN has a total of 65 nodes. The control volume method is used for mathematical modeling of heat exchange. The conceptual figure of the 65MN is illustrated in Figure 2-1. Heat is transferred through the tissues within individual segment by conduction. The body and the environment exchange heat by convection, radiation, evaporation, and respiration. Heat exchange between local tissues and blood flow is simplified as the heat exchange between local tissues and the central blood compartment. All the specific physiological parameters given as constants were assumed after the Stolwijk model weighted according the surface area ratio of further divided body segments. Surface area $A_{Du}(i)$[m^2] and weight[kg] of each body segment are shown in Table 2-1.

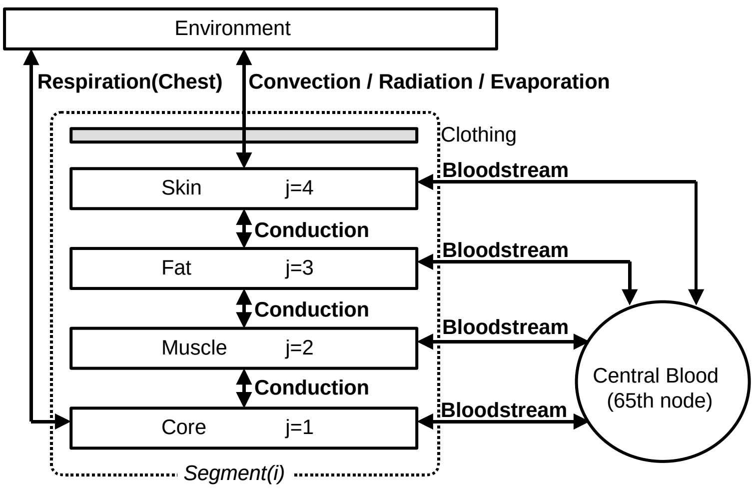


Figure 2-1. Conceptual figure of 65 MN

2.2.1 Heat Balance Equations of 65MN

The heat balance equations in four layers and central blood compartment are the followings:

- Core layer: $$C(i,1)\frac{dT(i,1)}{dt} = Q(i,1) - B(i,1) - D(i,1) - RES(i,1) \quad \ldots(2\text{-}1)$$

- Muscle layer: $$C(i,2)\frac{dT(i,2)}{dt} = Q(i,2) - B(i,2) + D(i,1) - D(i,2) \quad \ldots(2\text{-}2)$$

- Fat layer: $$C(i,3)\frac{dT(i,3)}{dt} = Q(i,3) - B(i,3) + D(i,2) - D(i,3) \quad \ldots(2\text{-}3)$$

- Skin layer: $$C(i,4)\frac{dT(i,4)}{dt} = Q(i,4) - B(i,4) + D(i,3) - Q_t(i,4) - E(i,4) \quad \ldots(2\text{-}4)$$

- Central blood: $$C(65)\frac{dT(65)}{dt} = \sum_{i=1}^{16}\sum_{j=1}^{4} B(i,j) \quad \ldots(2\text{-}5)$$

Each term in these equations will be described in the following sections.

1) Heat Capacity

$C(i,j)$[Wh/°C] is the heat capacity of node(i,j), and $T(i,j)$[°C] is its temperature. $C(i,j)$ calculated from the specific heat of tissues that constitute each node is shown in Table 2-2. The specific heat of individual tissue was assumed as follows: bone 0.580Wh/kg°C, fat 0.696Wh/kg°C, other tissues 1.044Wh/kg°C. Blood volume in the central blood compartment was assumed as 2.5L, as adopted by the Stolwijk Model.

Table 2-1. $A_{Du}(i)$[m^2] and weight[kg]

i	*Segment(i)*	$A_{Du}(i)$	Weight
1	Head	0.140	4.020
2	Chest	0.175	12.400
3	Back	0.161	11.030
4	Pelvis	0.221	17.570
5	L-Shoulder	0.096	2.163
6	R-Shoulder	0.096	2.163
7	L-Arm	0.063	1.373
8	R-Arm	0.063	1.373
9	L-Hand	0.050	0.335
10	R-Hand	0.050	0.335
11	L-Thigh	0.209	7.013
12	R-Thigh	0.209	7.013
13	L-Leg	0.112	3.343
14	R-Leg	0.112	3.343
15	L-Foot	0.056	0.480
16	R-Foot	0.056	0.480
-	Total	1.870	74.430

Table 2-2. $C(i,j)$[Wh/°C]

i	*Segment(i)*	Core	Muscle	Fat	Skin
1	Head	2.576	0.386	0.258	0.282
2	Chest	2.915	5.669	1.496	0.418
3	Back	2.471	5.022	1.322	0.386
4	Pelvis	6.017	7.997	2.102	0.606
5	L-Shoulder	0.503	1.078	0.207	0.151
6	R-Shoulder	0.503	1.078	0.207	0.151
7	L-Arm	0.321	0.681	0.131	0.099
8	R-Arm	0.321	0.681	0.131	0.099
9	L-Head	0.082	0.037	0.052	0.099
10	R-Head	0.082	0.037	0.052	0.099
11	L-Thigh	1.665	3.604	0.560	0.423
12	R-Thigh	1.665	3.604	0.560	0.423
13	L-Leg	0.793	1.715	0.268	0.204
14	R-Leg	0.793	1.715	0.268	0.204
15	L-Foot	0.139	0.037	0.077	0.125
16	R-Foot	0.139	0.037	0.077	0.125
-	Central Blood				2.610

2) Heat Production

$Q(i,j)$[W] is the rate of heat production expressed by Equation (2-6). $Q(i,j)$ is the sum of basal metabolic rate $Q_b(i,j)$[W], heat production by external work $W(i,j)$[W] and shivering heat production $Ch(i,j)$[W]. Heat production by external work and shivering only occurred in the muscle layer (j=2), and $Ch(i,j)=W(i,j)=0$ for other layers. Basal metabolic rate of each node is shown in Table 2-3.

$$Q(i,j)=Q_b(i,j)+W(i,j)+Ch(i,j) \quad \text{…(2-6)}$$

$$W(i,2)=58.2(met-Q_b)A_{Du}Metf(i) \quad \text{…(2-7)}$$

where, *met*[met] is the metabolic rate of the whole body, Q_b[met] is the basal metabolic rate and A_{Du}[m^2] is the surface area. Q_b is obtained from the sum of basal metabolic rate of all nodes: 0.778met. When the value of *W(i,2)* is negative, it is considered to be 0. *Metf(i)*[-] is the distribution coefficient of individual muscle layer for heat production by external work, and the values are also shown in Table 2-3.

Table 2-3. $Q_b(i,j)$[W] and *Metf(i)*[-]

i	*Segment(i)*	Core	Muscle	Fat	Skin	*Metf(i)*
1	Head	16.843	0.217	0.109	0.131	0.000
2	Chest	21.182	2.537	0.568	0.179	0.091
3	Back	18.699	2.537	0.501	0.158	0.080
4	Pelvis	8.050	4.067	0.804	0.254	0.129
5	L-Shoulder	0.181	0.423	0.610	0.050	0.026
6	R-Shoulder	0.181	0.423	0.610	0.050	0.026
7	L-Arm	0.094	0.220	0.031	0.026	0.014
8	R-Arm	0.094	0.220	0.031	0.026	0.014
9	L-Hand	0.045	0.022	0.023	0.050	0.005
10	R-Hand	0.045	0.022	0.023	0.050	0.005
11	L-Thigh	0.343	0.824	0.151	0.122	0.201
12	R-Thigh	0.343	0.824	0.151	0.122	0.201
13	L-Leg	0.102	0.220	0.035	0.023	0.099
14	R-Leg	0.102	0.220	0.035	0.023	0.099
15	L-Foot	0.122	0.035	0.056	0.100	0.005
16	R-Foot	0.122	0.035	0.056	0.100	0.005
-	Total				84.652	1.000

3) Heat Transfer by Blood Flow

B(i,j)[W] is the heat exchanged between each node and central blood compartment, and is expressed by Equation (2-8). α[-] is the ratio of counter-current heat exchange, and ρC[Wh/L°C] is the volumetric specific heat of blood. In this paper, it is assumed that α=1.000, ρC=1.067Wh/L°C. *BF(i,j)*[L/h] is the blood flow rate. Equation (2-9) expresses the blood flow rate for each layer except for skin. *T(65)*[°C] is the blood temperature in central blood compartment.

$$B(i,j) = \alpha \rho C \, BF(i,j)(T(i,j) - T(65)) \qquad \ldots(2\text{-}8)$$

$$BF(i,j) = BFB(i,j) + (W(i,j) + Ch(i,j))/1.16 \qquad \ldots(2\text{-}9)$$

In Equation (2-9), *BFB(i,j)*[L/h] is the basal blood flow rate, and values used in this model are shown in Table 2-4. It is assumed that the blood flow of 1.0L/h was required for 1.16W heat production.

Table 2-4. *BFB(i,j)*[L/h]

i	*Segment(i)*	Core	Muscle	Fat	Skin
1	Head	45.000	0.870	0.340	2.240
2	Chest	77.850	7.660	1.340	1.800
3	Back	76.340	7.660	1.340	1.350
4	Pelvis	18.190	12.280	2.160	2.080
5	L-Shoulder	0.320	1.280	0.160	0.860
6	R-Shoulder	0.320	1.280	0.160	0.860
7	L-Arm	0.160	0.670	0.085	0.450
8	R-Arm	0.160	0.670	0.085	0.450
9	L-Hand	0.091	0.078	0.042	0.910
10	R-Hand	0.091	0.078	0.042	0.910
11	L-Thigh	0.364	0.855	0.150	0.380
12	R-Thigh	0.364	0.855	0.150	0.380
13	L-Leg	0.071	0.070	0.019	0.110
14	R-Leg	0.071	0.070	0.019	0.110
15	L-Foot	0.049	0.010	0.019	0.450
16	R-Foot	0.049	0.010	0.019	0.450
-	Total	273.805			

4) Heat Exchange by Conduction

D(i,j)[W] is the heat transmitted by conduction to the adjacent layer within the same segment, and is expressed by Equation (2-10). *Cd(i,j)*[W/°C] is the thermal conductance between the node and its adjacent node. The values shown in Table 2-5 were used in this model.

$$D(i,j)=Cd(i,j)(T(i,j)-T(i,j+1)) \qquad \ldots(2\text{-}10)$$

Table 2-5. *Cd(i,j)*[W/°C]

i	*Segment(i)*	Core-Muscle	Muscle-Fat	Fat-Skin
1	Head	1.601	13.224	16.008
2	Chest	0.616	2.100	9.164
3	Back	0.594	2.018	8.700
4	Pelvis	0.379	1.276	5.104
5	L-Shoulder	0.441	2.946	7.308
6	R-Shoulder	0.441	2.946	7.308
7	L-Arm	0.244	2.227	7.888
8	R-Arm	0.244	2.227	7.888
9	L-Hand	2.181	6.484	5.858
10	R-Hand	2.181	6.484	5.858
11	L-Thigh	2.401	4.536	30.160
12	R-Thigh	2.401	4.536	30.160
13	L-Leg	1.891	2.656	7.540
14	R-Leg	1.891	2.656	7.540
15	L-Foot	8.120	10.266	8.178
16	R-Foot	8.120	10.266	8.178

5) Heat Loss by Respiration

The heat loss by respiration is assumed to occur only at the core layer of the chest segment, node*(2,1)*. *RES(2,1)*[W] is expressed by Equation (2-11).

$$RES(2,1)=\{0.0014(34-t_a(1))+0.017(5.867-p_a(1))\}\cdot\sum_{i=1}^{16}\sum_{j=1}^{4}Q(i,j) \qquad \ldots(2\text{-}11)$$

where, $t_a(1)$[°C] and $p_a(1)$[kPa] are air temperature and vapor pressure at the head segment respectively.

6) Evaporative Heat Loss at Skin Surface

E(i,4)[W] is evaporative heat loss at skin surface, and is expressed by Equation (2-12). $E_b(i,4)$[W] is the heat loss by water vapor diffusion through the skin. The skin diffusion is assumed to be 6% of $E_{max}(i)$, as shown in Equation (2-13). In the Stolwijk model, values of $E_b(i,4)$ are given as constants, which correspond to about 3-4% of $E_{max}(i)$. E_{sw}(i,4)[W] is the heat loss by evaporation of sweat.

$$E(i,4)=E_b(i,4)+E_{sw}(i,4) \qquad \text{…(2-12)}$$

$$E_b(i,4)=0.06(1-E_{sw}(i,4)/E_{max}(i))\, E_{max}(i) \qquad \text{…(2-13)}$$

where, $E_{max}(i)$[W] is maximum evaporative heat loss, and is shown by Equation (2-14).

$$E_{max}(i)=h_e(i)\,(p_{sk,s}(i)-p_a(i))A_{Du}(i) \qquad \text{…(2-14)}$$

$$h_e(i)=LR\cdot i_{cl}(i)\Big/\left(0.155I_{cl}(i)+\frac{i_{cl}(i)}{h_c(i)\cdot f_{cl}(i)}\right) \qquad \text{…(2-15)}$$

where, $h_e(i)$[W/m^{2}kPa] is the evaporative heat transfer coefficient from the skin surface to the environment, expressed as a function of clothing vapor permeation efficiency $i_{cl}(i)$[-] by Equation (2-15). $p_{sk,s}(i)$[kPa] is the saturated vapor pressure on the skin surface, $p_a(i)$[kPa] is the ambient vapor pressure, and $A_{Du}(i)$[m^2] is the surface area of the body segment.

In Equation (2-15), $I_{cl}(i)$[clo] and $f_{cl}(i)$[-] are clothing insulation and clothing area factor for individual segment respectively, derived from the thermal manikin experiment. The Stolwijk model does not take into account the clothing insulation. $h_c(i)$[W/m^2°C] is the convective heat transfer coefficient between the clothing and the environment, and *LR*[°C/kPa] is the Lewis relation coefficient.

7) Sensible Heat Exchange at Skin Surface

$Q_t(i,4)$[W] is convective and radiant heat exchange rate between the skin surface and the environment, described by Equation (2-16). $h_t(i)$[W/m^2°C] is the total heat transfer coefficient from the skin surface to the environment, and is expressed by Equation (2-17) in which $t_o(i)$[°C] is the operative temperature, and $h_r(i)$[W/m^2°C] is the radiant heat transfer coefficient. Convective and radiant heat transfer coefficients were derived from the thermal manikin experiment [6].

$$Q_t(i,4)=h_t(i)(T(i,4)- t_o(i))A_{Du}(i) \qquad \ldots(2\text{-}16)$$

$$\frac{1}{h_t(i)} = 0.155 I_{cl}(i) + \frac{1}{(h_c(i)+h_r(i))f_{cl}(i)} \qquad \ldots(2\text{-}17)$$

2.2.2 Control System of 65MN

1) Sensor Signals

The error signal *Err(i, j)*[°C] is calculated by Equation (2-18). The set-point temperature $T_{set}(i,j)$[°C], which plays a role of "control target temperature", is determined on Table 2-6.

$$Err(i,j)=(T(i,j)-T_{set}(i,j))+RATE(i,j)\ F(i,j) \qquad \text{…(2-18)}$$

where, *RATE(i,j)*[h] is the dynamic sensitivity of thermoreceptor, and *F(i j)*[°C/h] is the temperature change rate. Since quantitative analysis of the value for *RATE (i,j)* is not clear yet, it is set to be 0 in this paper.

Warm signal *Wrm(i,j)*[°C] and cold signal *Cld(i,j)*[°C], corresponding to warm and cold receptors respectively, are defined by Equation (2-19) (when *Err(i, j)*>0) and Equation (1-20) (when *Err(i, j)*<0).

$$Wrm(i,j)=Err(i,j),\ Cld(i,j)=0 \qquad \text{…(2-19)}$$

$$Cld(i,j)=-Err(i,j), Wrm(i,j)=0 \qquad \text{…(2-20)}$$

Table 2-6. $T_{set}(i,j)$[°C]

i	*Segment(i)*	Core	Muscle	Fat	Skin
1	Head	36.9	36.1	35.8	35.6
2	Chest	36.5	36.2	34.5	33.6
3	Back	36.5	35.8	34.4	33.2
4	Pelvis	36.3	35.6	34.5	33.4
5	L-Shoulder	35.8	34.6	33.8	33.4
6	R-Shoulder	35.8	34.6	33.8	33.4
7	L-Arm	35.5	34.8	34.7	34.6
8	R-Arm	35.5	34.8	34.7	34.6
9	L-Hand	35.4	35.3	35.3	35.2
10	R-Hand	35.4	35.3	35.3	35.2
11	L-Thigh	35.8	35.2	34.4	33.8
12	R-Thigh	35.8	35.2	34.4	33.8
13	L-Leg	35.6	34.4	33.9	33.4
14	R-Leg	35.6	34.4	33.9	33.4
15	L-Foot	35.1	34.9	34.4	33.9
16	R-Foot	35.1	34.9	34.4	33.9
-	Central Blood	36.7(Initial Temperature)			

2) Integrated Signal

It is supposed that integrated sensor signals from skin thermoreceptors are used as the control variable. Integrated warm signal (*Wrms*[°C]) and integrated cold signal (*Clds*[°C]) are defined by Equation (2-21) and (2-22). *SKINR(i)*[-] is the weighting factor for integration, and is shown in Table 2-7.

$$Wrms = \sum_{i=1}^{16} (SKINR(i) \cdot Wrm(i,4)) \qquad \ldots(2\text{-}21)$$

$$Clds = \sum_{i=1}^{16} (SKINR(i) \cdot Cld(i,4)) \qquad \ldots(2\text{-}22)$$

Table 2-7. Weighting and distribution factor[-]

i	*Segment(i)*	*SKINR(i)*	*SKINS(i)*	*SKINV(i)*	*SKINC(i)*	*Chilf(i)*
1	Head	0.070	0.081	0.132	0.022	0.020
2	Chest	0.149	0.146	0.098	0.065	0.258
3	Back	0.132	0.129	0.086	0.065	0.227
4	Pelvis	0.212	0.206	0.138	0.065	0.365
5	L-Shoulder	0.023	0.051	0.031	0.022	0.004
6	R-Shoulder	0.023	0.051	0.031	0.022	0.004
7	L-Arm	0.012	0.026	0.016	0.022	0.026
8	R-Arm	0.012	0.026	0.016	0.022	0.026
9	L-Hand	0.092	0.016	0.061	0.152	0.000
10	R-Hand	0.092	0.016	0.061	0.152	0.000
11	L-Thigh	0.050	0.073	0.092	0.022	0.023
12	R-Thigh	0.050	0.073	0.092	0.022	0.023
13	L-Leg	0.025	0.036	0.023	0.022	0.012
14	R-Leg	0.025	0.036	0.023	0.022	0.012
15	L-Foot	0.017	0.018	0.050	0.152	0.000
16	R-Foot	0.017	0.018	0.050	0.152	0.000
-	Total	1.000	1.000	1.000	1.000	1.000

2.2.3 Thermoregulatory System of 65MN

All control equations consist of 3 terms. One is related with head core signal, another with skin signal, and the third term is related with both. The thermoregulatory system is constituted of four control processes: vasodilation, vasoconstriction, perspiration, and shivering heat production. The distribution coefficient [-] of individual segment for each control process is also shown in Table 2-8. The control coefficients are shown in Table 8, used in Equations (2-24), (2-25), (2-27) and (2-28). When the values for *DL*, *ST*, $E_{sw}(i.4)$, *Ch(i,2)* calculated from control equations become negative, they are set to be 0.

Table 2-8. Control coefficients

	Core(*C*)		Skin(*S*)		Core×Skin(*P*)	
Sweat(*sw*)	*Csw* [W/°C]	371.2	*Ssw* [W/°C]	33.6	*Psw* [W/°C^2]	0.0
Shivering(*ch*)	*Cch* [W/°C]	0.0	*Sch* [W/°C]	0.0	*Pch* [W/°C^2]	24.4
Vasodilation(*dl*)	*Cdl* [L/h°C]	117.0	*Sdl* [L/h°C]	7.5	*Pdl* [L/h°C^2]	0.0
Vasoconstriction(*st*)	*Cst* [1/°C]	11.5	*Sst* [1/°C]	11.5	*Pst* [1/°C^2]	0.0

1) Vasomotion

Skin blood flow $BF(i,4)$[L/h] is calculated by Equation (2-23). DL[l/h] and ST[-] are the signals respectively for vasodilation (Equation (2-24)) and vasoconstriction (Equation (2-25)).

$$BF(i,4) = \frac{BFB(i,4) + SKINV(i) \cdot DL}{1 + SKINC(i) \cdot ST} \cdot km(i,4) \qquad \ldots(2\text{-}23)$$

$$DL = CdlErr(1,1) + Sdl(Wrms - Clds) + PdlWrm(1,1)Wrms \qquad \ldots(2\text{-}24)$$

$$ST = -\ CstErr(1,1)\ -\ Sst(Wrms - Clds) + PstCld(1,1)Clds \qquad \ldots(2\text{-}25)$$

In Equation (2-23) and (2-27), $km(i,4)$[-] is called the "local multiplier", a factor for incorporating the effect of local skin temperature on vasomotion and perspiration, defined by Equation (2-26). $RT(i,4)$[°C] is the temperature range required for $km(i,4)$ to be 2. In this paper, value of $RT(i,4)$ was considered to be 10°C for all segments.

$$km(i,4) = 2.0^{Err(i,4)/RT(i,4)} \qquad \ldots(2\text{-}26)$$

2) Perspiration

The heat loss by evaporation of sweat $E_{sw}(i,4)$[W] is calculated by Equation (2-27).

$$E_{sw}(i,4) = \{CswErr(1,1) + Ssw(Wrms - Clds) + PswWrm(1,1)Wrms\}\ SKINS(i)\ km(i,4) \qquad \ldots(2\text{-}27)$$

3) Shivering Heat Production

The shivering heat production *Ch(i,2)*[W] is calculated by Equation (2-28).

$$Ch(i,2)=\{ - CchErr(1,1) - Sch(Wrms-Clds)+PchCld(1,1)Clds\}\ Chilf(i) \quad \text{…(2-28)}$$

Chilf(i)[-] is the distribution coefficient of individual muscle layer for the shivering heat production, shown in Table 2-7.

2.2.4 Calculation of SET* by 65MN

*65MNSET** is calculated from the output values of mean skin temperature, skin wettedness, and total heat loss from skin surface, based on 65MN. *65MNSET**, derived from the calculation with constants and coefficients in this paper, agreed well with conventional SET* under uniform thermal environment. Moreover, *65MNSET** can be applied to the non-uniform thermal conditions.

2.3 DEVELOPMENT OF MOBILE MEASUREMENT CART

A mobile measurement cart is developed to measure the thermal environment around a walking person, passing through one environment to another. The highest measurement point of mobile measurement carts for office surveys is 1.1 m, corresponding to the head height of a seated person, but the height of the present cart is extended to 1.7 m, corresponding to the head height of a standing (walking) person. The present cart is an improved version of the latest one used for past studies by Hayashi et al. (1996), and realized lightweight, easy assembly, and compactness for easier transportation. The cart is depicted in Figures 2-2 and 2-3, and Table 2-9 shows the specific items for the measurements. These items and methods for measurements were based on ISO-7726 and ASHRAE 55-92. Dry cell batteries were used to allow this cart for relocation after each measurement without plugging to the commercial AC line. Table tennis balls painted gray were used to measure the mean radiant temperature. The following equation was used to calculate mean radiant temperature from globe temperature (Benton et al., 1990):

$$T_r = \left[\frac{6.32 \cdot d^{-0.4} \cdot v^{0.5}}{\sigma\varepsilon} (T_g - T_a) + T_g{}^4 \right]^{0.25} \qquad \ldots(2\text{-}29)$$

where

d	: diameter of the globe (m)
ε	: emissivity of the globe
σ	: Stephan-Boltzmann constant (5.67 x 10^{-8} W/m^{2}K^4)
T_a	: air temperature (K)
T_g	: globe temperature (K)
T_r	: mean radiant temperature (K)
v	: air velocity (m/s)

Figure 2-3. Mobile measurement cart in operation

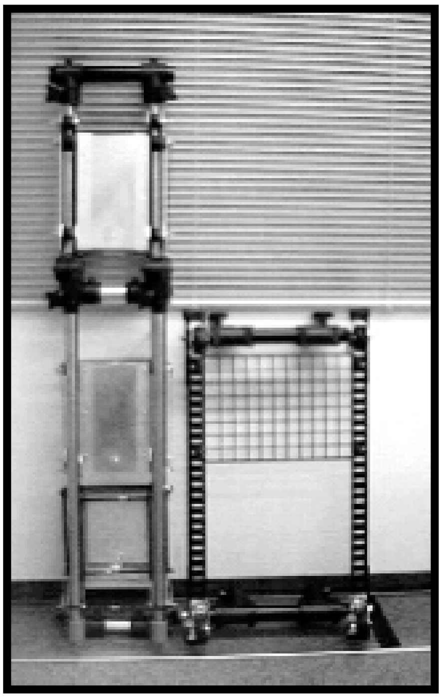


Figure 2-4. Mobile measurement cart folded for transportation

Table 2-9. Items of measurements

Item	Instrument	Height (m)
Air temperature	C-C thermocouples	0.1, 0.6, 1.1, 1.7
Globe temperature	Globe thermometer	0.1, 0.6, 1.1, 1.7
Relative humidity	TDK relative humidity sensor	1.1
Air velocity	Indoor climate analyzer (B&K1213) RION AM-03 (for outdoor)	0.1, 0.6, 1.1, 1.7 1.1
Solar radiation	ML-020V (Eiko-Seiki)	1.1
Radiant temperature	Indoor climate analyzer (B&K1213)	1.1
Floor surface temperature	Indoor climate analyzer (B&K1213)	0

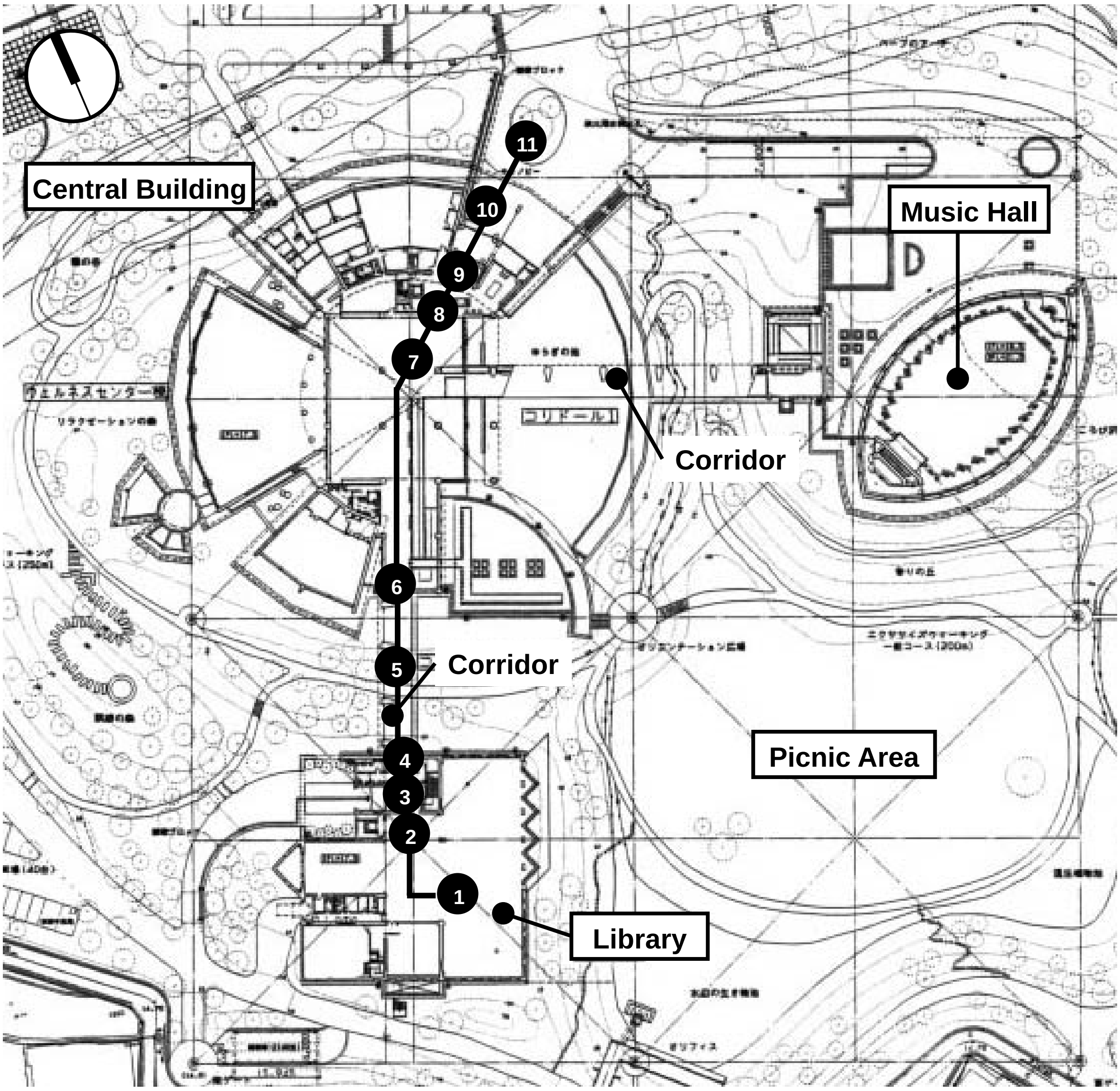
2.4 FIELD MEASUREMENT OF TRANSITIONAL THERMAL ENVIRONMENT

2.4.1 Method

The objective of the present survey was to investigate how different routes affected the thermal environment experienced by a walking person, and to collect environmental data of semi-outdoor environment for boundary conditions of numerical simulation with 65MN.

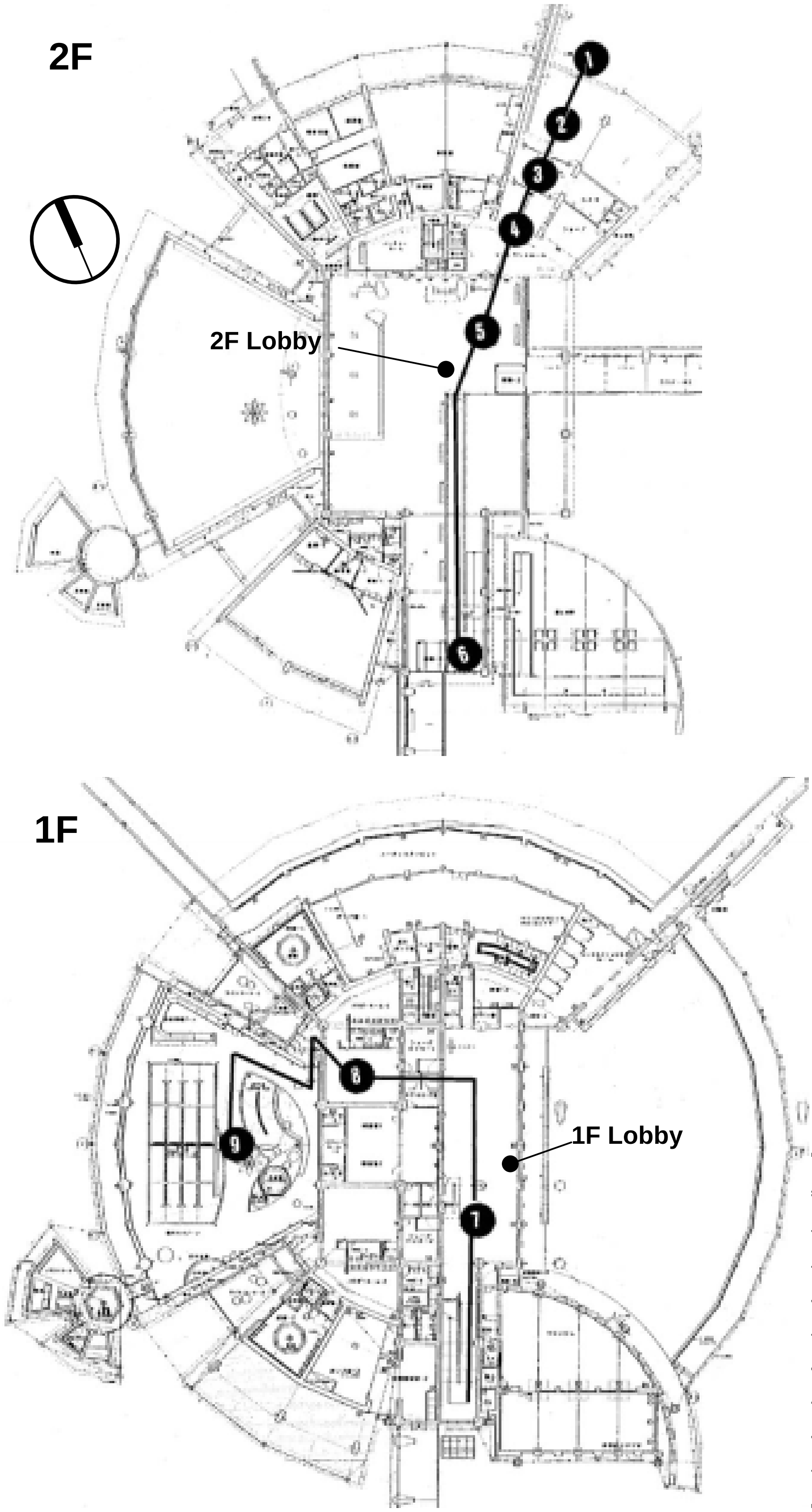
Total of three seasonal field measurements were conducted at an integrated facility located in Hyogo Prefecture (long. 134° 50’E, lat. 34° 45’N), Japan. Summer survey was conducted from August 20 to 22, 1997, autumn survey on October 27 and 28, 1997, and winter survey on January 8 and 9, 1998. The site plan of the entire facility is given in Figure 2-4. This facility was placed on the south side of a hill, consisting of a central building with fitness club, a library, and a music hall. The three buildings were connected by open corridors. The main entrance of the central building was located on the second floor, facing northeast. Second floor lobby and first floor lobby, connected by slope way, formed an atrium with huge windows facing east. Floor plans are illustrated in Figure 2-5.

Measurement points were determined along several virtual routes, supposing a visitor moving through the facility for different destinations. Mobile measurement cart was utilized to quantify the thermal environment at representative points along the route. At each point, environmental variables given in Table 2-11 were measured every 30 seconds for 10 minutes. Average values of whose within the last three minutes were used for analysis. The results of the “pool route” and the “library route” are reported. The “pool route” simulated a visitor heading towards the indoor swimming pool on the first floor through the main entrance on the second floor of the central building. The “library route” starts from the library building, passing through the central building, and going out of the main entrance. The measurement points are described in detail in Figures 2-4 and 2-5.



No.	Building	Library Route
1	Library	Reading room
2	Library	Stairway
3	Library	2F lobby
4	Library	Windshield room
5		Corridor
6	Central	Windshield room
7	Central	2F lobby Atrium
8	Central	Entrance hall
9	Central	Windshield room
10	Central	Outside of 2F entrance
11	Central	Outdoor

Figure 2-4. Site plan of hte facility and measurement points for the library route



No.	Pool Route	
1	Outdoor	
2	Outside of 2F entrance	
3	Windshield room	
4	Entrance hall	
5	2F lobby	
6	Slope	Atrium
7	1F lobby	
8	Locker room	
9	Indoor swimming pool	

Figure 2-5. Second and first floor plans of the facility. The numbers indicate the measurement points of the “pool route”.

2.4.2 Results of Field Measurement

1) Environmental Variation Profiles for the Two Routes

The results of thermal environment measurement of the pool route and the library route in winter are presented in Figures 2-6 and 2-7 respectively. Air temperature and air velocity at four heights, and mean radiant temperature and humidity at 1.1m are presented. The distance between each measurement point is reflected on the X-axis. The pool route is a transition process within the central building. Gradual rises of air temperature and mean radiant temperature was observed as the distance from the entrance was longer, and the environment was deeper into the core of the building. Maximum vertical temperature difference was observed in 2F lobby, 3.1 °C between 0.1 and 1.1 m above floor level. The measurement was conducted before noon, and the space was in the midst of rapid preheating process. Air velocity was also observed to be higher than other spaces due to the same reason. The library route requires transitions in and out of the building, resulting in air temperature step changes of more than 10 °C for a total of 3 times. Mean radiant temperature and air velocity were high in the corridor. The afternoon-measurement of this route was the reason for large mean radiant temperature difference between corridor and outside of the 2F entrance. The 10 minutes required for measurement of each representative environment had caused a time lag of more than an hour between the 2 outdoor measurements, and the setting winter sun had lost its effect at the entrance facing northeast. Shorter measurement period is desired for mobile measurement of long routes. Nevertheless, differences in thermal environment variation profile could be quantified using the mobile measurement cart.

The air temperature of the non air-conditioned windshield rooms were found to be the intermediate value of the adjacent indoor and outdoor environments, confirming its effect on the spaces as thermal buffer zones.

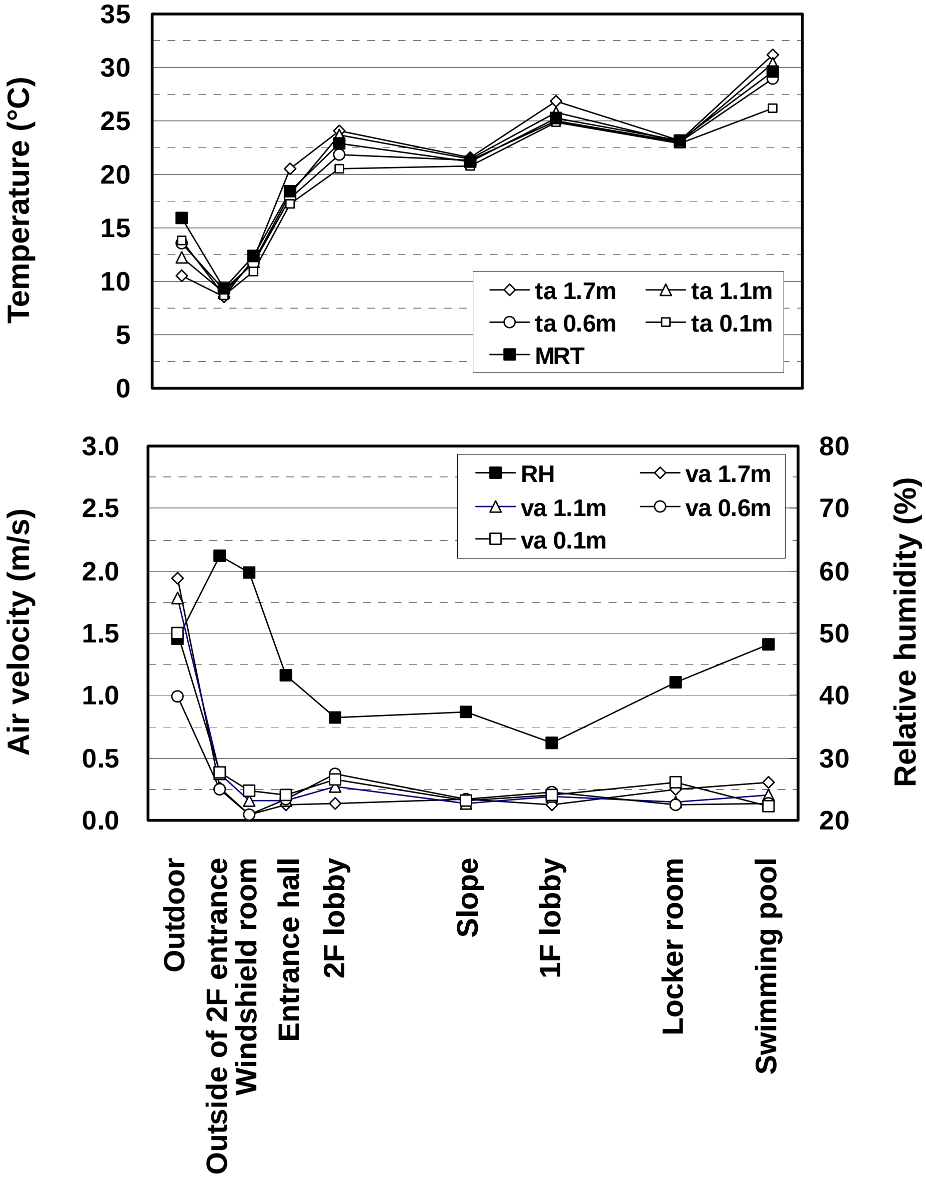


Figure 2-6. Environmental variation profile of the pool route in winter

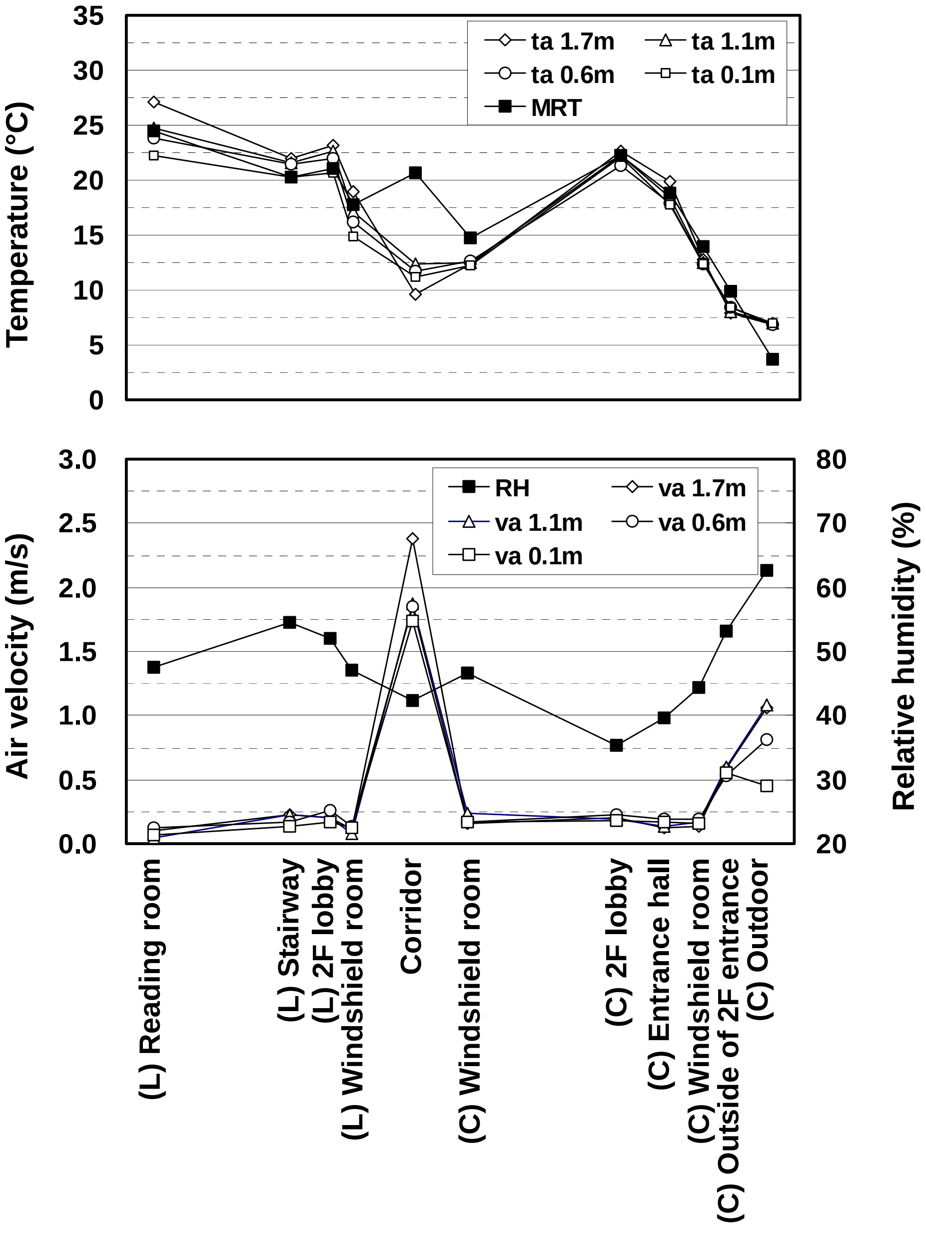


Figure 2-7. Environmental variation profile of the library route in winter

2) Seasonal Differences

Figure 2-8 shows the comparison of three seasonal results of pool route measured in summer, autumn, and winter. The air temperature and mean radiant temperature measured at the height of 1.1 m are plotted. The seasonal differences of air temperature and mean radiant temperature measured at 1F lobby, locker room, and indoor swimming pool were small, indicating sufficiently controlled thermal environment throughout the year. In summer, the values of air temperature and mean radiant temperature fell gradually as the cart moved inside of the facility. On the other hand, the temperatures were observed to rise in winter. In autumn, the change of thermal environment was relatively smaller, owing to the natural ventilation utilized during the intermediate seasons. Although the thermal environments were quite different at the beginning of the route among the three seasons, air temperature and mean radiant temperature became closer after passing through the 1F lobby.

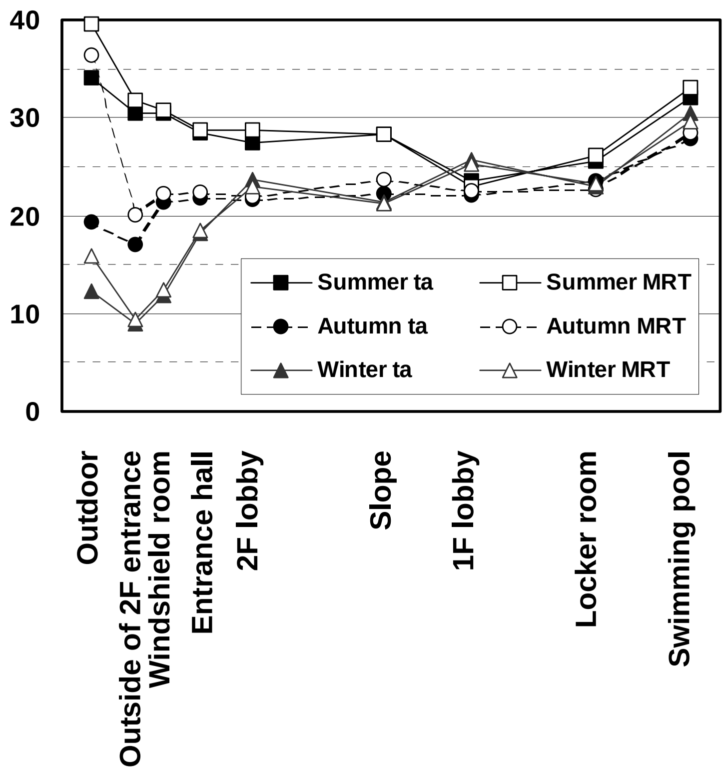


Figure 2-8. Seasonal differences of air temperature (ta) and mean radiant temperature (MRT) for the pool route

2.5 65MN SIMULATION WITH FIELD MEASUREMENT DATA

The discrete measurement data acquired from the filed survey was used as boundary conditions of the numerical simulation by 65MN to simulate the transient physiological conditions of a person undergoing continuous environmental step changes. The environmental variables at four heights were applied to each of the 16 body segments for corresponding heights. Clothing insulation measured by thermal manikin (Tanabe et al., 1994) was used for clo values. The duration of each environment was given according to the distance between each representative measurement points, divided by walking speed of 0.89 m/s (3.2 km/h). The initial warm up conditions were set at the environment of 25 °C air temperature and mean radiant temperature, 50 % rh, and 0.10 m/s air velocity with 1.0 met. Considering the relative increase of air velocity, 0.89 m/s was added while walking. The effect of environmental composition on transient physiological conditions was investigated

2.5.1 The Summer Pool Route (Case 1)

The environmental data of the pool route was used to compare the physiological conditions between a passer-by and an occupant staying in the environment. The boundary conditions are given in Table 2-10. The first two phases will be referred to as “outdoor”, the next 4 phases from windshield room to slope as “buffer”, and the rest as “indoor”. A passer-by was simulated to pass through the environment for the period given in the table, while an occupant was supposed to stay in the environment for 60 minutes. The results of mean skin temperature (*Msk*) and evaporative heat loss (*E*) are given in Figure 2-9. Discrete plots represent the physiological variable of an occupant. Fast *Msk* rise of a passer-by in the first 15 minutes was regulated by the start of sweat secretion. The rapid decrease began as a passer-by entered the buffer environment, and the value was stable when entering indoor environment. Although the evaporative heat loss of a passer-by closely matched with that of an occupant, *Msk* tended to be higher for a passer-by due to the residual heat stored outside. Alternative conditions were examined, supposing that thermal environment of outdoor was under the thermally comfortable conditions, same as the warm up conditions. *Msk* of comfortable conditions coincided with the initial outdoor conditions at the end of buffer phases. The buffer environment was able to cancel out body-stored heat in 15 minutes.

Table 2-10. Boundary condition for Case 1

	Phase no.	Measurement point	Duration period (min.)	Metabolic rate (met)	Clothing (clo) Summer	Change
Outdoor	1	Outdoor	30	2.0	0.55	env.
	2	Outside of 2F entrance	2	2.0	0.55	env.
Buffer	3	Windshield room	1	2.0	0.55	env.
	4	Entrance hall	2	2.0	0.55	env.
	5	2F lobby	4	2.0	0.55	env.
	6	Slope	3	2.0	0.55	env.
Indoor	7	1F lobby	3	2.0	0.55	env.
	8	Locker room	5	1.6	0.55	env.
	9		5	1.6	0	clo.
	10	Indoor swimming pool	5	1.2	0	env.
	11		5	2.4	0	met.

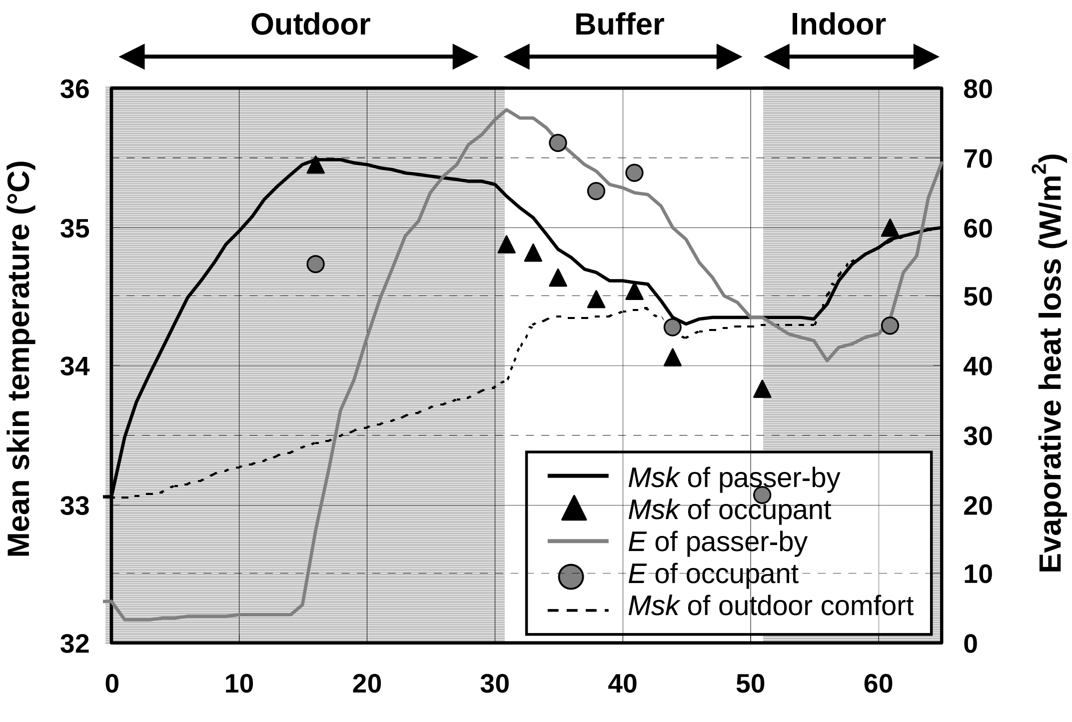


Figure 2-9. Calculated mean skin temperature and evaporative heat loss for Case 1

2.5.2 Seasonal Variation and Space Composition (Case 2)

Two virtual "pool routes" were supposed for each season: the long route and the short route. The long route allowed the visitor to pass through the buffer zones before reaching the swimming pool, while the short route visitor entered the 1F lobby straight from outdoor. Tables 2-11 and 2-12 show the boundary conditions for two routes consisting of several phases. Figure 2-10 presents the mean skin temperature and evaporative heat loss of an imaginary visitor heading for the swimming pool along two different routes. "Season-L" and "Season-S" in the figure represent the results for long route and short route in each season respectively. *Msk* at the end of outdoor phase, just before entering indoor, and at the beginning of pool phase, the destination of the visitor, are given in Table 2-13 for each route. Msk variation rates are also presented. Because of the differences in clothing, initial *Msk* and *E* in each season were slightly different. In summer and autumn when indoor and outdoor air temperatures were close, slight difference was observed between the short route and the long route. In winter, on the other hand, higher *Msk* was observed for the long route visitor at the beginning of the pool phase. *Msk* variation rate was also smaller, indicating a gradual change of the thermal environment as opposed to the short route. The buffer zones were confirmed to alleviate heat shocks upon entering or leaving indoor and this function became more effective when differences in thermal environment were large between indoor and outdoor.

The results of the local skin temperature simulation for Cases 1 and 2 are depicted in Figures 2-11 and 2-12.

Table 2-11. Boundary conditions for the “long route”

Phase no.	Measurement point	Supposed time (min.)	Met	Clothing (clo)			Change mode to next phase
				Summer	Autumn	Winter	
1	Outdoor	30	2	0.55	0.82	1.25	Step
2	Outside of entrance	2	2	0.55	0.82	1.25	Step
3	Wind shield room	1	2	0.55	0.82	1.25	Step
4	Entrance	2	2	0.55	0.82	1.25	Step
5	2F lobby	4	2	0.55	0.82	1.25	Step
6	Slope	3	2	0.55	0.82	1.25	Step
7	1F lobby	3	2	0.55	0.82	1.25	Step
8	Locker room	5	1.6	0.55	0.82	1.25	Step
9		5	1.6	0	0	0	Step
10	Indoor swimming pool	15	1.6	0	0	0	-

Table 2-12. Boundary conditions for the “short route”

Phase no.	Measurement point	Supposed time (min.)	Met	Clothing (clo)			Change mode to next phase
				Summer	Autumn	Winter	
1	Outdoor	30	2	0.55	0.82	1.25	Step
2	1F lobby	3	2	0.55	0.82	1.25	Step
3	Locker room	5	1.6	0.55	0.82	1.25	Step
4		5	1.6	0	0	0	Step
5	Indoor swimming pool	27	1.6	0	0	0	-

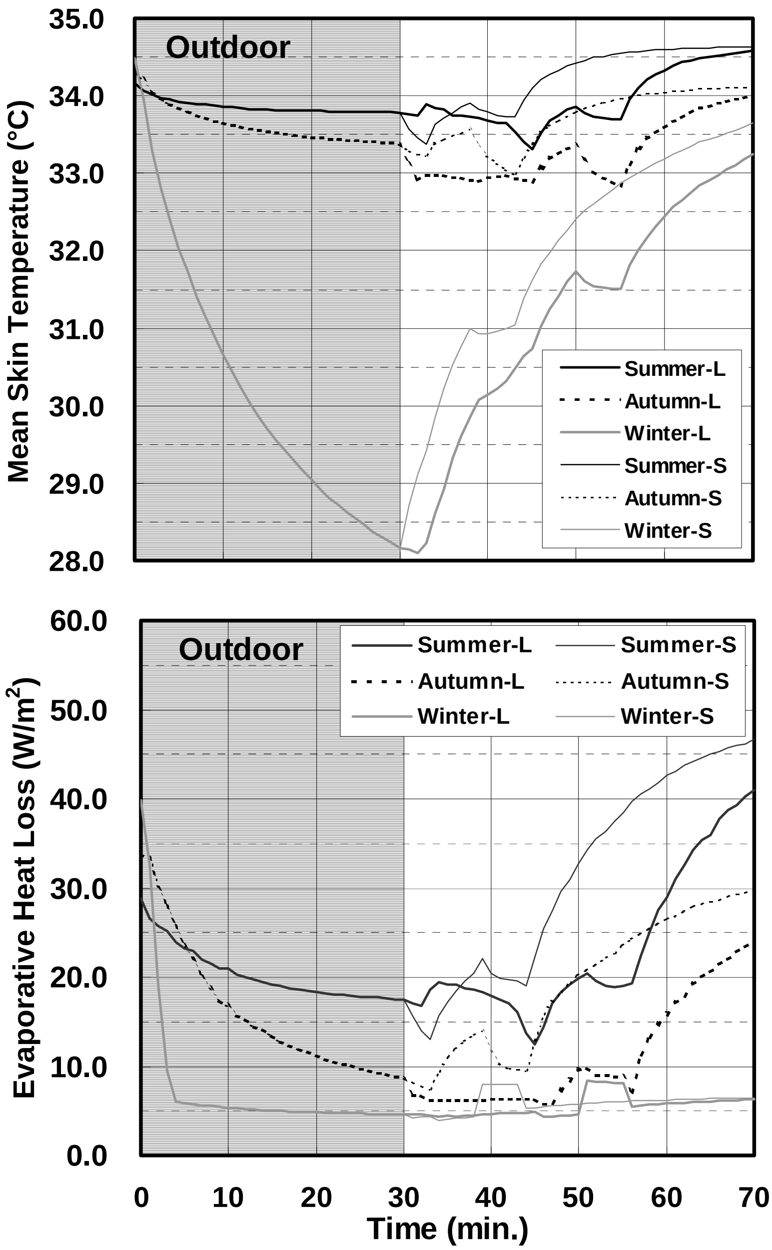


Figure 2-10. Mean skin temperature and evaporative heat loss profiles of Case 2

Table 2-13. Mean skin temperature and variation rate for each route

	Long route			Short route		
	Summer	Autumn	Winter	Summer	Autumn	Winter
End of outdoor phase	33.8 °C	33.4 °C	28.2 °C	33.8 °C	33.4 °C	28.2 °C
Start of pool phase	34.0 °C	33.1 °C	31.8 °C	33.9 °C	33.2 °C	31.4 °C
MST variation rate (°C/min.)	0.01	-0.01	0.14	0.01	-0.01	0.23

Figure 2-11. Skin temperature difference in Case 1.
Passer-by (left) and occupant (right) in the 2F lobby.

Figure 2-12. Skin temperature difference in Case 2.
Short route passé-by on left and long route on right

2.6 CONCLUSION

Evaluation method for transient thermal comfort was proposed, integrating field measurement of environmental variables and numerical simulation of human thermoregulation. Numerical thermoregulation model, 65MN, was presented to examine the transient physiological response during transition. The mobile field measurement apparatus for acquisition of thermal environmental variables in successive environments was developed. Seasonal field measurements were carried out along several imaginary routes for summer, autumn, and winter at an integrated public facility in Hyogo, Japan. Using these physical data as boundary conditions, numerical simulation of physiological conditions was performed utilizing the 65-node model. The buffer zones were confirmed to reduce the influence of outdoor thermal environment especially when the differences were large between outdoor and indoor. Because outdoor conditions of the summer measurements were moderate, distinct effects of buffer zones could not be explicitly confirmed in summer. The results were interpreted from the mean skin temperature variation rates of a simulated visitor, but further investigation is required to clarify the relationship between simulated physiological variables and the actual thermal sensation or comfort sensation.

CHAPTER 3

TRANSIENT THERMAL COMFORT SUCCEEDING A SHORT WALK IN A BUFFER SPACE FROM OUTDOOR TO INDOOR

CHAPTER 3 TRANSIENT THERMAL COMFORT SUCCEEDING A SHORT WALK IN A BUFFER SPACE FROM OUTDOOR TO INDOOR

3.1 INTRODUCTION

People experience a large step change of thermal environment when entering or leaving an architectural environment, especially in summer and winter when the temperature differences are large between indoor and outdoor. Semi-outdoor environments acting as thermal buffer spaces such as entrance halls and atriums are often built to mitigate these sudden environmental differences, besides aesthetic aspects. Although there exists no thermal environmental guideline for designing these buffer spaces, it is very likely that the thermal environment in the buffer space would have large effects on impression and thermal comfort in a succeeding environment. The purpose of this study is to evaluate the effect of thermal environmental condition of a buffer space on thermal comfort in a succeeding environment.

A subjective experiment was designed to simulate an occupant leaving indoor space through a buffer space to outdoor space, and back. Summer condition was chosen for outdoor space since the effect of buffer space is expected to be larger in summer when occupants sweat and wear a fewer amount of clothing. The conceptual drawing of the experiment is depicted in Figure 3-1.

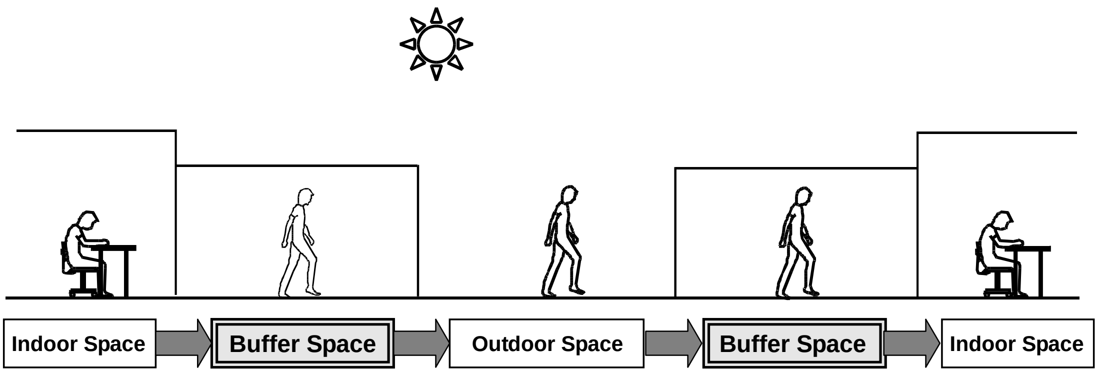


Figure 3-1. Conceptual figure of the experiment

3.2 OUTLINE OF EXPERIMENT

3.2.1 Experimental Schedule

Experiments were conducted from September 21 to October 21, 2000, in a climate chamber in Waseda University, Japan. Every experimental day was divided into 3 sessions starting from 9:00, 13:00 and 17:00. Subjects participated in the same period for all the experimental conditions. The climate chamber was divided into 3 spaces to simulate the thermal environment for indoors, buffer space and outdoors. Plan of the climate chamber and pictures from the experiment are depicted in Figure 3-2.

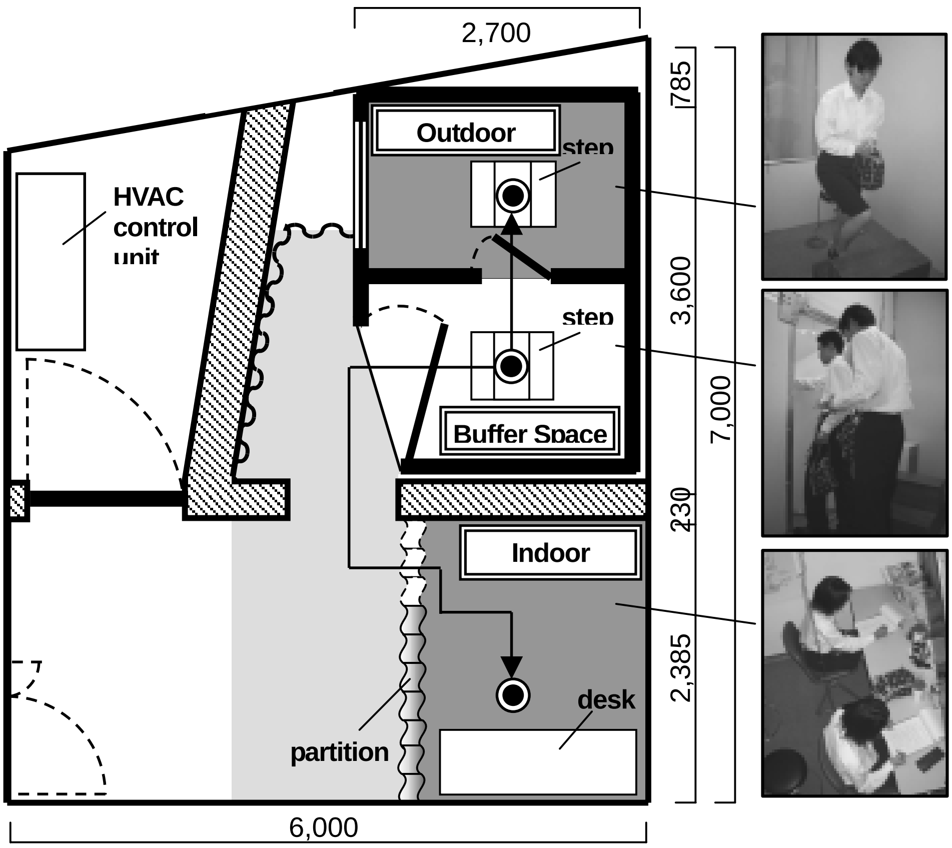


Figure 3-2. Plan of the climate chamber and pictures from the experiment

3.2.2 Subjects

The body-build data of the subjects, 6 males and 6 females, are given in Table 3-1. Subjects wore a set of typical office attire prepared by the experimenter: long sleeved Y shirt, sleeveless undershirt, tie, pants, sox, underwear, and leather shoes for males and long sleeved blouse, underwear, skirt, pantyhose, and leather shoes for females. The clothing ensemble was measured with a thermal manikin and found to be 0.72 clo (standing), 0.77 clo (seated, chair included) for males and 0.58 clo (standing), 0.64 clo (seated, chair included) for females.

Table 3-1. Body-build data of the subjects

	Height (m)		Weight (kg)		A_{Du} (m^2)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
Male	1.74	0.05	60.2	5.1	1.73	0.09
Female	1.61	0.06	50.6	5.6	1.52	0.11

3.2.3 Experimental Conditions

The thermal environment of the spaces were controlled at 32 °C, 70 %RH for outdoors and 25 °C, 50-60 %RH for indoors. Buffer space was controlled at 3 conditions of 22, 25, 28 °C, and transition period was set at 3, 5, and 10 minutes. A combination of these variables and a condition without a buffer zone yielded a total of 10 experimental conditions as given in Table 3-2. Other thermal environment variables of the buffer space were controlled as follows: air temperature = mean radiant temperature, 50-60 %RH, still air. The average environmental data of each space measured every 2 minutes are given in Table 3-3.

Table 3-2. Experimental condition codes

		Duration			
		0 min.	3 min.	5 min.	10 min.
Air temp.	22 ºC		22-3	22-5	22-10
	25 ºC	25-0	25-3	25-5	25-10
	28 ºC		28-3	28-5	28-10

Table 3-3. Average environmental data of each space

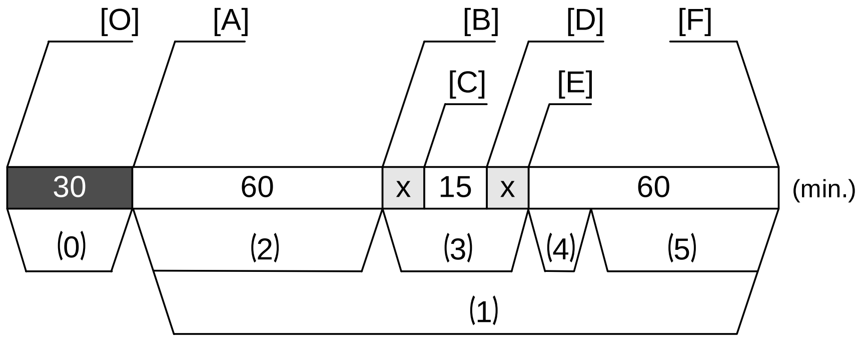
	Indoor Space			Buffer Space			Outdoor Space		
	Target	Mean	(S.D.)	Target	Mean	(S.D.)	Target	Mean	(S.D.)
Air temp. (ºC)	25	25.0	(0.7)	28	28.1	(0.2)	32	32.2	(0.1)
		24.9	(0.5)	25	25.0	(0.2)		32.0	(0.2)
		24.9	(0.5)	22	21.9	(0.3)		32.1	(0.6)
Relative humidity (%)		53	(5)		56	(1)	70	70	(1)
		58	(3)		59	(1)		70	(2)
		53	(2)		58	(2)		68	(1)

3.2.4 Experimental Method

Subjects made a series of transition in the following order: indoor space (60 min.) – buffer space (3, 5, or 10 min.) – outdoor space (15 min.) – buffer space (3, 5, or 10 min.) – indoor space (60 min.). Transition period of the buffer zone was fixed for each experimental condition. No more than 2 subjects participated in each session. Metabolic rate was controlled by step exercise (Arens et al., 1993) at 2.0 met in buffer space and outdoor space to simulate walking at the speed of 3.2 km/h (ASHRAE, 2002), and 1.2 met to simulate regular office work in indoor space. In “23-0” condition, subjects walked through the buffer space controlled at 25 °C to make a transition from indoor to outdoor space. Following the time schedule given in Figure 3-3, subjects were asked to mark a line on the questionnaire given in Figure 3-4. Questionnaire items were defined as “environmental temperature sensation vote (ESV)”, “whole body thermal sensation vote (TSV)”, “comfort sensation vote (CSV)”, “sweat sensation”, “clothing acceptability”, “wet body part”, and “thermal acceptability” in the order presented in the questionnaire. When the subjects returned to the indoor space after a series of transitions, they were asked to vote every minute for a period of 10 minutes to follow the rapid variation in sensation.

A concept of “environmental temperature sensation vote (ESV)” and “whole body thermal sensation vote (TSV)” was introduced in this experiment. TSV is the widely accepted concept to describe the thermal state of the subject in a given thermal environment. However, when a subject undergoes a step change through different thermal environments, the rapid environmental change itself may be sensed as hot / warm / cool / cold in comparison to the preceding environment and consequently affect the thermal sensation vote. In order for subjects to consciously distinguish the 2 different concepts of thermal sensation, two separate scales were used.

Mean skin temperatures of all the subjects were measured every 10 seconds with C-C thermocouples attached to forehead, abdomen, left thigh, left leg, left foot, left arm and left hand. Vapor pressures within clothing were recorded simultaneously by attaching relative humidity sensors at chest and back. Body temperature at armpit and weight were also measured at the beginning and end of each experiment.



* Value of "x" corresponds to experimental condition (0, 3, 5, 10)

[O]	Antechamber	(0)	Change cloth, attach physiological sensors
[A]	Experiment start Indoor space phase	(1)	Skin temperature, vapor pressure measurement / every 10 sec.
		(2)	Desk work / vote every 10 min.
[B]	Buffer space phase	(3)	Step exercise / vote upon leaving and entering each space
[C]	Outdoor space phase		
[D]	Buffer space phase	(4)	Desk work / vote every 1 min. (10min. after entrance)
[E]	Indoor space phase		
[F]	End of experiment	(5)	Desk work / vote every 5 min.

Figure 3-3. Experimental procedure

1. How do you feel the ENVIRONMENT to be?

-3	-2	-1	0	+1	+2	+3
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

2. How do you feel YOURSELF to be?

-3	-2	-1	0	+1	+2	+3
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

3. Do you feel the present ENVIRONMENT to be comfortable or uncomfortable?

-3	-2	-1	0	+1	+2	+3
Very Un-comfortable	Uncomfort-able	Slighly Un-comfortable	Neutral	Slighly Comfortable	Comfortable	Very Comfortable

4. Are you SWEATING right now?

0	+1	+2	+3
Not Swating	Slighly Sweating	Sweating	Very much Sweating

5. Do you find the condition of your CLOTHING to be acceptable or unacceptable?

-1		0		+1
Clearly Unacceptable	Just Unacceptable		Just Acceptable	Clearly Acceptable

6. Which BODY SEGMENT do you feel to be wet due to sweating?

None Stomach Neck Chest Back Arm pit Leg Knee Others ( )

7. Do you find the THERMAL ENVIRONMENT to be acceptable or unacceptable?

-1		0		+1
Clearly Unacceptable	Just Unacceptable		Just Acceptable	Clearly Acceptable

Figure 3-4. Voting Sheet

3.3 RESULTS

All analyses on psychological and physiological variables were conducted based on mean values of 6 males and 6 females.

3.3.1 Psychological Variables

3.3.1.1 Transition Phase

Figure 3-5 presents the variation in ESV, TSV and CSV throughout the experiment. The 10 minute transition conditions likely to be most affected by the environmental condition of buffer space are presented as representative. Unstable votes for the first 30 minutes were omitted. Large variations were observed for all the votes throughout the transition process, especially females, partly because of the lower clothing insulation compared to males. Due to large differences before and after the transition, analyses were focused on the transition phase to investigate the characteristics of psychological variables in this section

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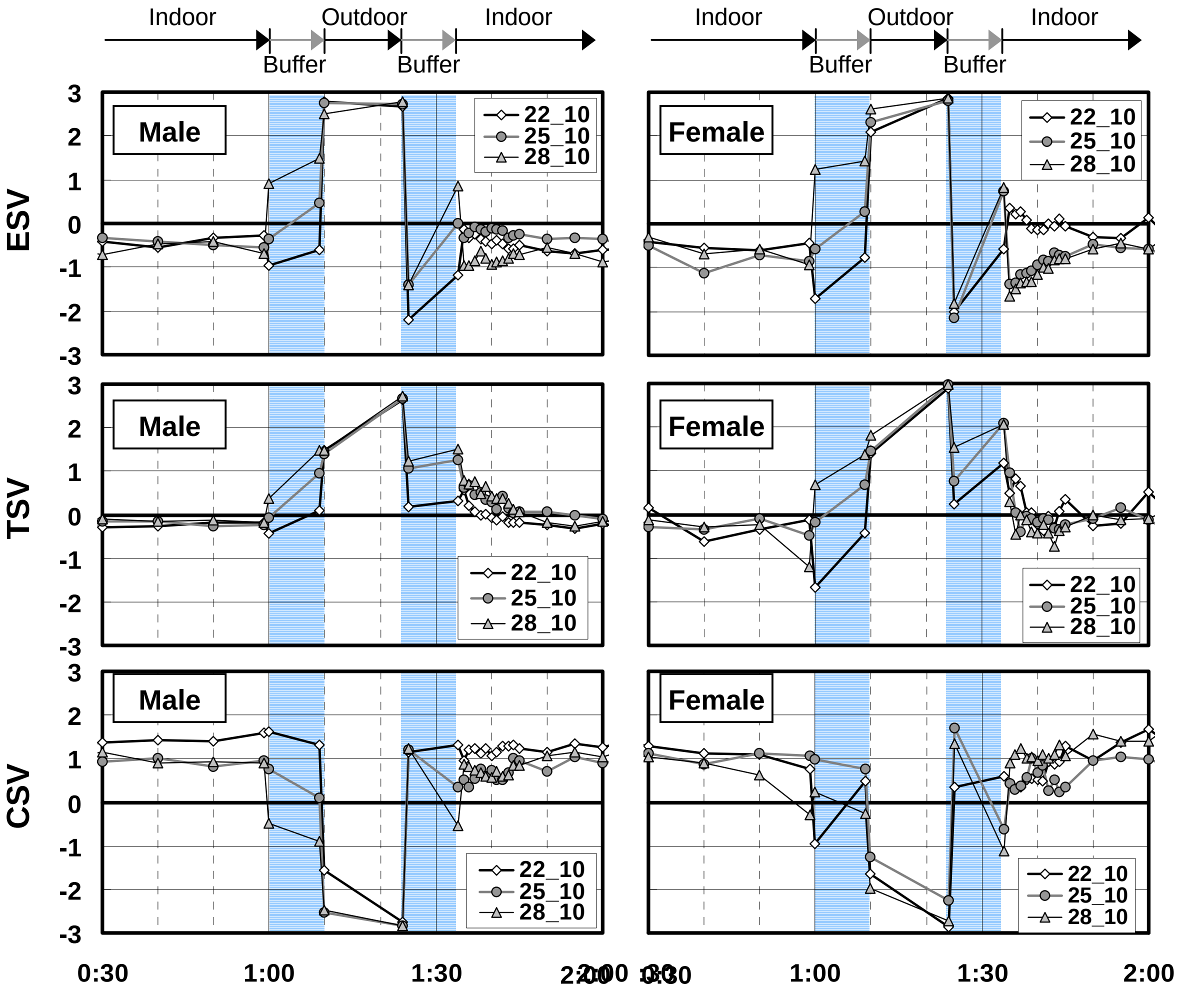


Figure 3-5. ESV, TSV, and CSV during transition phase (10 minute transition)

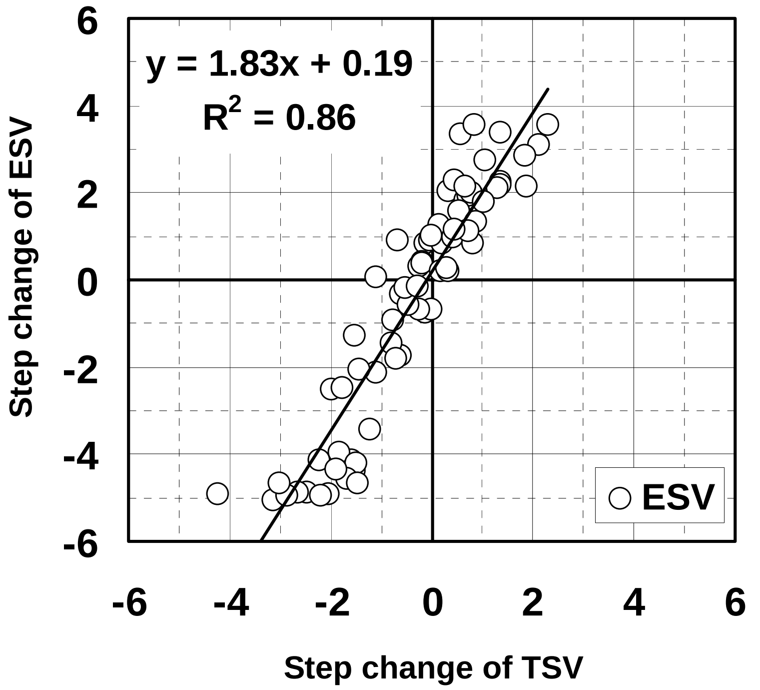


Figure 3-6. Step change in TSV and ESV

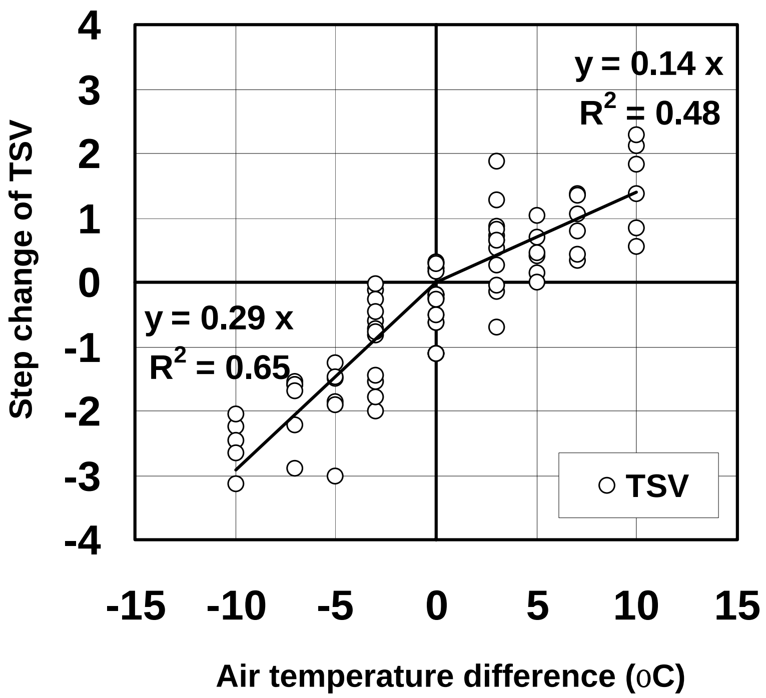


Figure 3-7. Air temperature difference and step change in TSV

The differences in ESV before and after the transition of each space are plotted against differences in TSV in Figure 3-6. The change in scale unit is twice as large for ESV than TSV, indicating that ESV is more sensitive to a given step change in thermal environment. Figure 3-7 depicts the TSV against temperature change, showing that subjects were more sensitive to lower temperature changes than higher temperature changes.

Relationship between ESV, TSV and CSV are presented in Figure 3-8 for step changes toward 22, 25, and 28 °C. No correlation was found between the voted values, but a high correlation in scale unit difference was found for both thermal sensation votes and CSV during transition to thermally neutral condition (25 °C), especially when the differences were larger. CSV seems to increase when ESV and TSV changes are negative due to the present experimental condition, but correlation is lower on step changes towards 22 and 28 °C. The difference in transition time accounts to the difference in the amount of activity, and this may have effected how the subjects felt the same temperature change.

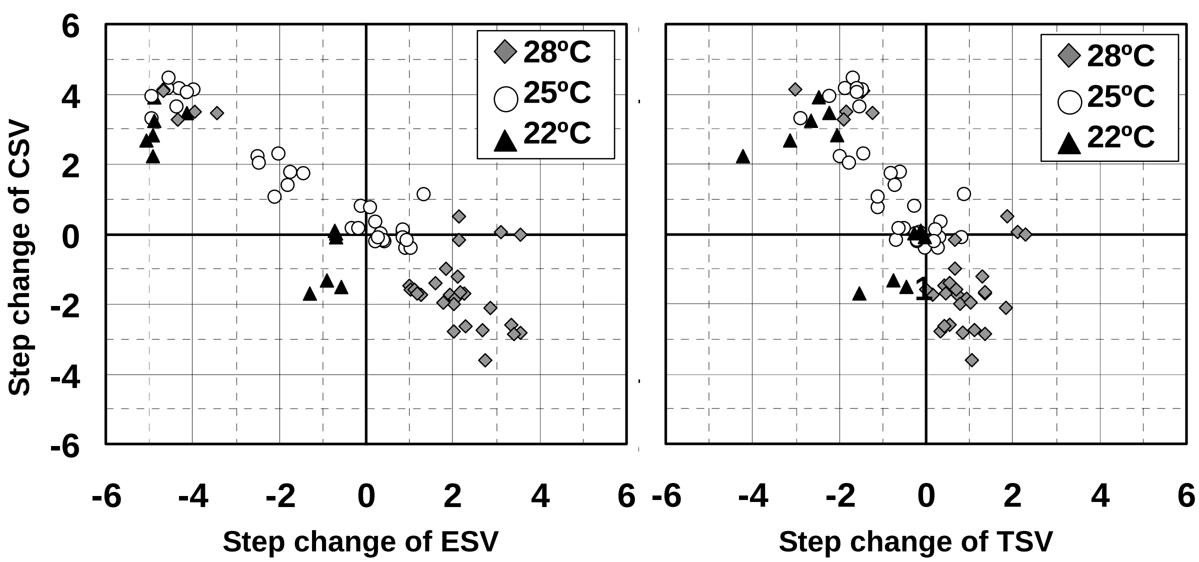


Figure 3-8. Step change of CSV against step change of ESV and TSV

3.3.1.2 Occupancy Phase

Steady-state votes during the occupancy phase in indoor space calculated from average of the last 20 minutes are given in Table 3-4 for ESV, TSV and CSV before and after the transition. Paired t test yielded no significant difference for ESV and TSV before and after the transition. The only significant difference found was CSV for “28-10” condition for both male and female ($p<0.01$). The thermal environment and transition time of buffer space was confirmed to have very small effect on psychological variables after 40 minute occupancy. ESV was significantly lower than TSV during occupancy phase ($p<0.01$) with average difference of 0.4 for males and 0.3 for females.

Table 3-4. Steady-state votes in indoor space before and after the transition

			22-3	25-3	28-3	22-5	25-5	28-5	22-10	25-10	28-10	25-0
ESV	Male	before	-0.3	-0.6	-0.8	-0.7	-0.7	-0.5	-0.4	-0.5	-0.5	-0.7
		after	-0.5	-0.6	-0.8	-0.7	-0.8	-0.6	-0.5	-0.6	-0.7	-0.6
	Female	before	-0.8	-0.1	-0.5	-0.7	-0.5	-0.8	-0.5	-0.9	-0.7	-0.1
		after	-0.1	0.0	-0.4	-0.7	-0.4	-0.6	-0.2	-0.8	-0.2	-0.5
TSV	Male	before	0.0	-0.1	-0.1	-0.2	-0.2	0.1	-0.2	-0.2	-0.1	-0.4
		after	-0.2	-0.2	-0.2	-0.3	-0.3	-0.2	-0.3	-0.3	-0.4	-0.3
	Female	before	-0.4	0.2	0.0	-0.3	-0.5	-0.8	-0.4	-0.3	-0.6	0.2
		after	0.1	0.2	-0.3	-0.2	0.0	-0.4	0.0	-0.4	0.1	-0.3
CSV	Male	before	1.2	0.6	0.6	0.9	0.9	0.9	1.5	0.9	0.9	0.6
		after	1.4	1.2	0.9	1.3	1.2	1.0	1.4	1.2	1.3	1.3
	Female	before	1.0	1.4	1.1	0.7	1.1	1.0	1.0	1.0	0.4	0.8
		after	1.2	1.7	1.0	0.7	1.2	1.4	1.6	0.9	1.6	0.5

3.3.2 Physiological Variables

3.3.2.1 Mean Skin Temperature

Steady-state values during the occupancy phase in indoor space calculated from the average of the last 20 minutes and maximum values in outdoor space are given in Table 3-4 for all experimental conditions. Mean skin temperature of females was significantly 1 °C lower than males. Random differences were also found between experimental conditions before the transition. Therefore, analyses on mean skin temperature were based on the variation from the steady state value in indoor space before the transition. Mean skin temperature variation are given in Figure 3-9 for 10 minute transition conditions without buffer condition.

Mean skin temperature began to rise upon entering the buffer zone, with the exception 22 °C conditions and “23-10” of males. The values reached maximum before leaving outdoor space, decreased rapidly in the order of 28, 25, 22 °C on entering the buffer space, and gradually reached the steady-state value in the indoor space. The maximum values in the outdoor space were similar for all conditions with the average of 35.4 °C for males and 35.0 °C for females. Mean skin temperature of females in indoor space was significantly higher after the transition ($p<0.01$). The step exercise throughout the experiment has contributed to the noticeable rise in lower body parts such as legs, thighs, and foot.

Table 3-5. Representative values of mean skin temperature

[ºC]		22-3	25-3	28-3	22-5	25-5	28-5	22-10	25-10	28-10	25-0
"Indoor" steady-state before transition	Male	34.2 (0.6)	34.2 (0.4)	34.1 (0.6)	34.1 (0.5)	34.6 (0.5)	34.5 (0.5)	34.0 (0.4)	34.3 (0.5)	34.1 (0.3)	34.4 (0.4)
	Female	33.4 (0.3)	33.6 (0.5)	33.7 (0.5)	33.4 (0.5)	33.1 (0.6)	33.5 (0.8)	33.5 (0.6)	33.1 (0.7)	33.0 (0.8)	33.4 (0.7)
"Indoor" steady-state after transition	Male	34.4 (0.4)	34.2 (0.2)	34.3 (0.4)	34.3 (0.2)	34.4 (0.4)	34.0 (0.3)	33.9 (0.4)	34.0 (0.3)	33.8 (0.4)	34.5 (0.4)
	Female	33.6 (0.4)	34.0 (0.4)	34.0 (0.6)	34.0 (0.1)	33.6 (0.5)	33.7 (0.4)	33.7 (0.6)	33.5 (0.7)	33.5 (0.8)	33.7 (0.7)
"Outdoor" maximum	Male	35.3 (0.4)	35.3 (0.2)	35.5 (0.4)	35.3 (0.4)	35.6 (0.3)	35.5 (0.3)	35.3 (0.3)	35.4 (0.3)	35.3 (0.1)	35.6 (0.3)
	Female	34.9 (0.4)	35.1 (0.2)	35.2 (0.5)	35.1 (0.3)	35.1 (0.4)	35.3 (0.4)	35.0 (0.4)	34.8 (0.7)	35.0 (0.5)	34.9 (0.4)

(S.D)

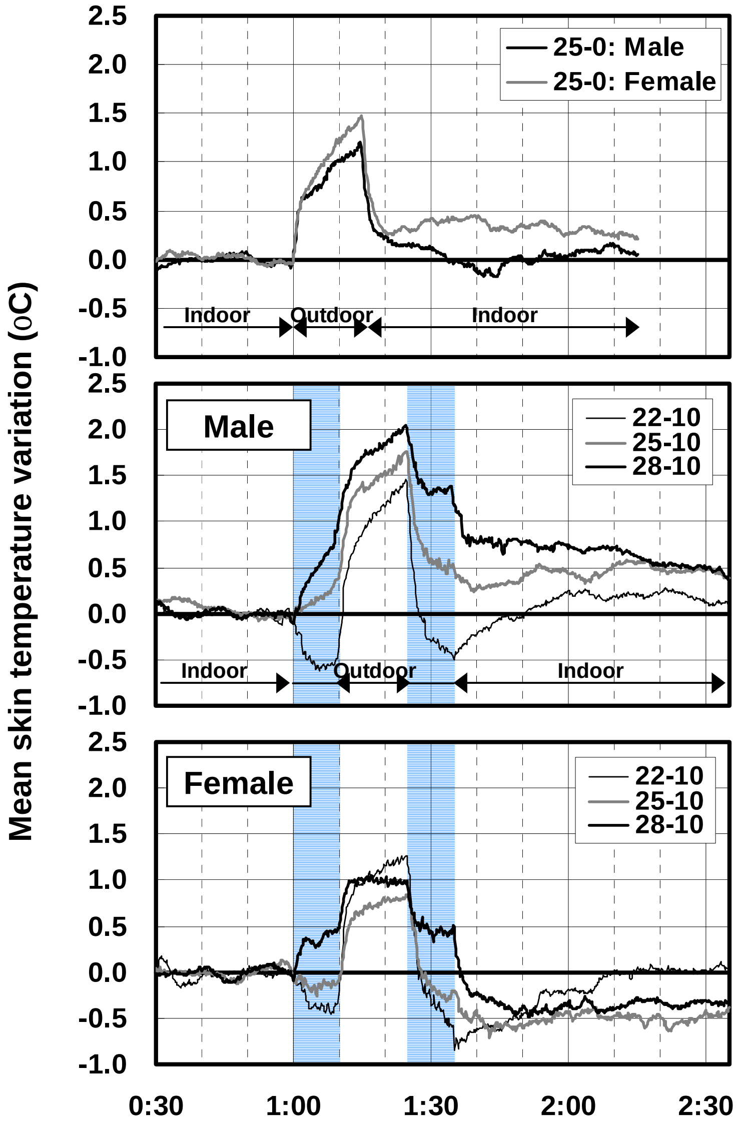


Figure 3-9. Mean skin temperature variation from standard value
(10 minute transition and no buffer condition)

3.3.2.2 Vapor Pressure Inside Clothing

The representative values calculated in the same way as mean skin temperature are given in Table 3-6. The steady state value before the transition were similar for all conditions. Average values were 2.2 kPa for males and 1.9 kPa for females, and significant difference were found between males and females ($p<0.01$).

Variation in vapor pressure inside clothing is given in Figure 3-10. The value for both males and females started to rise as the transition started, and maximum value was observed before leaving outdoor space, similar to mean skin temperature. The vapor pressure dropped in the buffer zone after outdoor space due to the change in environmental humidity, but shortly started to rise again due to the step exercise before entering indoor space. At this point, vapor pressure inside clothing was higher in the order of environmental temperature of buffer space. The decrease of females was greater than males in indoor space, and reached the steady state value by the end of experiment. Males had approximately 1 kPa higher values than pre-transition indoor space. Males were wearing cotton undershirt which absorbed their sweat, and consequently resulted in a slow decrease of vapor pressure inside clothing.

Vapor pressure inside clothing had strong correlation with sweat sensation and clothing acceptability as depicted in Figure 11. Females had a high clothing acceptability rate when the vapor pressure was low, but when it exceeded 4.0 kPa, sweat sensation was higher than 1 and clothing acceptability was voted on the unacceptable side. On the other hand, males mainly voted sweat sensation to be higher than 1 and clothing acceptability to be acceptable at even 4.5 kPa. Males were found to be more tolerant of the vapor pressure inside clothing, but clothing acceptability was never fully acceptable, supposedly due to uneasiness caused by the clothing itself such as necktie.

Table 3-6. Representative values of vapor pressure inside clothing

[kPa]		22-3	25-3	28-3	22-5	25-5	28-5	22-10	25-10	28-10	25-0
"Indoor" steady-state before transition	Male	2.1 (0.4)	2.3 (0.4)	2.0 (0.2)	2.3 (0.3)	2.2 (0.0)	2.1 (0.3)	2.1 (0.1)	2.2 (0.3)	2.2 (0.4)	2.2 (0.2)
	Female	1.8 (0.1)	2.0 (0.2)	1.8 (0.1)	1.9 (0.1)	2.0 (0.2)	1.8 (0.1)	1.9 (0.1)	1.8 (0.1)	1.8 (0.2)	2.0 (0.1)
"Indoor" steady-state after transition	Male	2.7 (0.7)	3.1 (0.8)	3.2 (0.8)	2.9 (0.6)	3.5 (0.6)	3.9 (0.8)	3.0 (0.8)	3.9 (0.8)	4.1 (0.6)	2.9 (0.8)
	Female	1.7 (0.1)	2.0 (0.2)	1.8 (0.1)	2.0 (0.1)	2.2 (0.3)	2.0 (0.2)	2.1 (0.1)	2.5 (0.3)	2.3 (0.2)	2.1 (0.1)
"Outdoor" maximum	Male	4.9 (0.5)	5.0 (0.4)	5.2 (0.7)	4.9 (0.4)	5.5 (0.3)	5.4 (0.5)	5.0 (0.5)	5.3 (0.5)	5.5 (0.4)	4.8 (0.7)
	Female	4.4 (0.1)	4.9 (0.2)	4.9 (0.4)	4.8 (0.4)	4.9 (0.4)	4.9 (0.4)	4.8 (0.3)	5.0 (0.2)	5.2 (0.3)	4.9 (0.3)

(S.D)

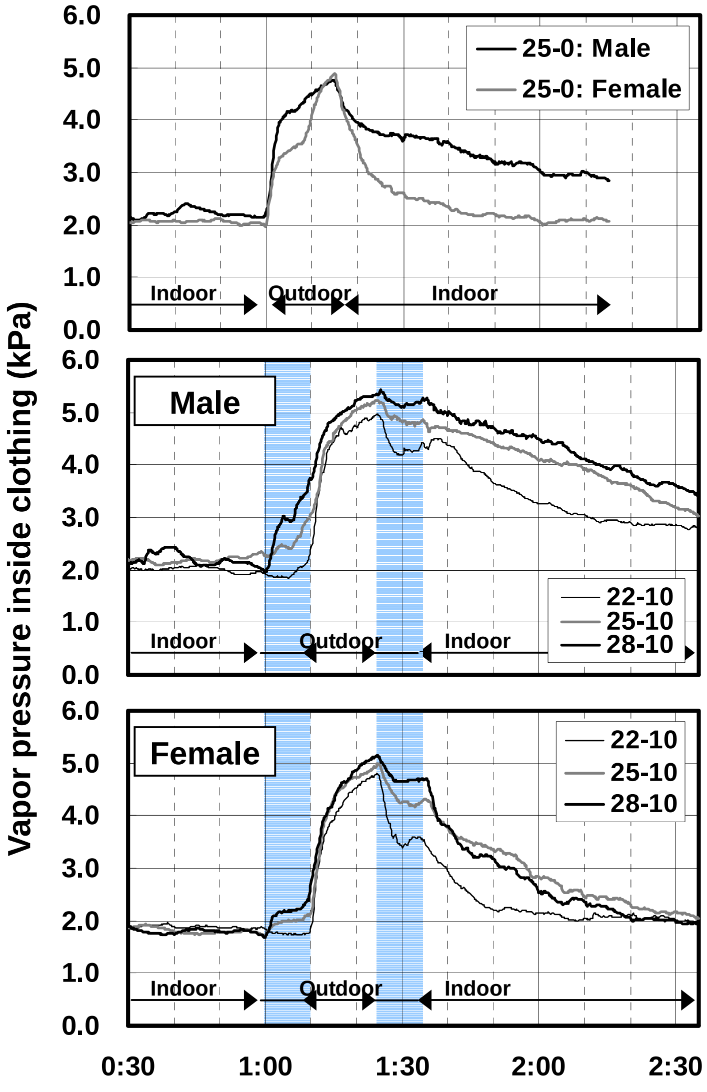


Figure 3-10. Variation in vapor pressure inside clothing

(10 minute transition and no buffer condition)

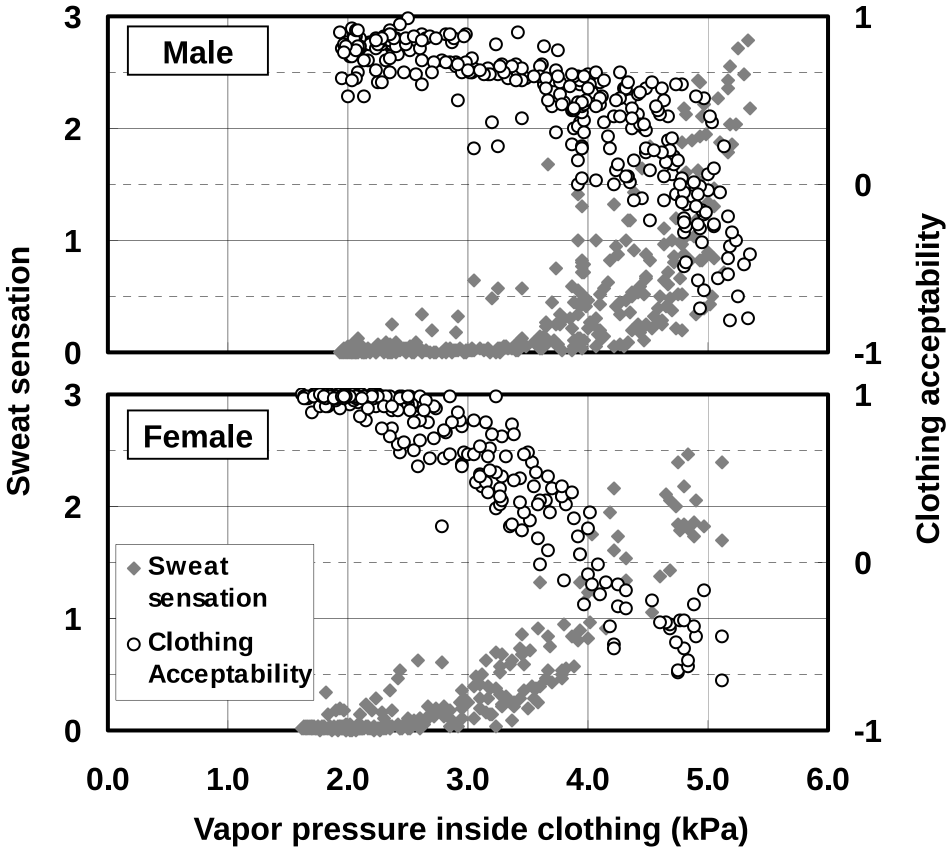


Figure 3-11. Sweat sensation and clothing acceptability against vapor pressure inside clothing

3.3.3 Effect of Environmental Condition of Buffer Space

In every experimental condition, psychological and physiological variables were found to be maximum or minimum when leaving the outdoor space, and the values were similar. Effects of environmental conditions of buffer space was investigated focusing on the latter transition process from outdoor space to indoor space through buffer space. Slight difference was found between 3 minute and 5 minute transition conditions, and comparison was sought between 3 minute, 10 minute condition and no buffer condition.

3.3.3.1 Psychological Variables

Figure 3-12 presents the variation of ESV, TSV, and CSV in post-transition indoor space, with the point of entrance as being 0 minute.

1) Environmental Temperature Sensation Vote

In such conditions as no buffer (23-0) and 28 °C where the indoor space temperature is relatively lower than the preceding environment, votes were low upon entrance, but gradually reached neutrality. On the other hand, votes of 25 °C and 28 °C conditions except for 23-10 of females were observed to be nearly constant at all times. Significant difference in the first vote upon entrance was found between the no buffer condition and 25 and 28 °C conditions except for 23-10 of females (paired t test, $p<0.01$). Effect of transition time was not significant within the same temperature conditions. Temperature of the buffer space was found to have the dominating effects on ESV.

2) Whole body Thermal Sensation Vote

Male votes decayed gradually to reach thermal neutrality within 10 minutes after entrance for all conditions. Female votes were observed to drop after about 5 minutes and rise again to reach thermal neutrality except for 22-3. Decay of vapor pressure inside clothing was greater for females than males, and rapid evaporative heat loss caused the vote to drop in the early period after entrance. The largest vapor pressure drop of 1.4 kPa in the first 5 minutes was observed for 23-0 condition, and TSV at fifth minute was found to have a significant difference with all 3 minute conditions ($p<0.05$).

3) Comfort Sensation Vote

All votes of males and females in indoor space were within the comfortable side of the neutral for all conditions. None of the experimental conditions were found to have a significant difference with 23-0, but several patterns in CSV variation were observed during the first 20 minutes: 1) High upon entrance, sudden drop, and recovery, 2) low upon entrance and gradual recovery, 3) constant throughout at a certain level.

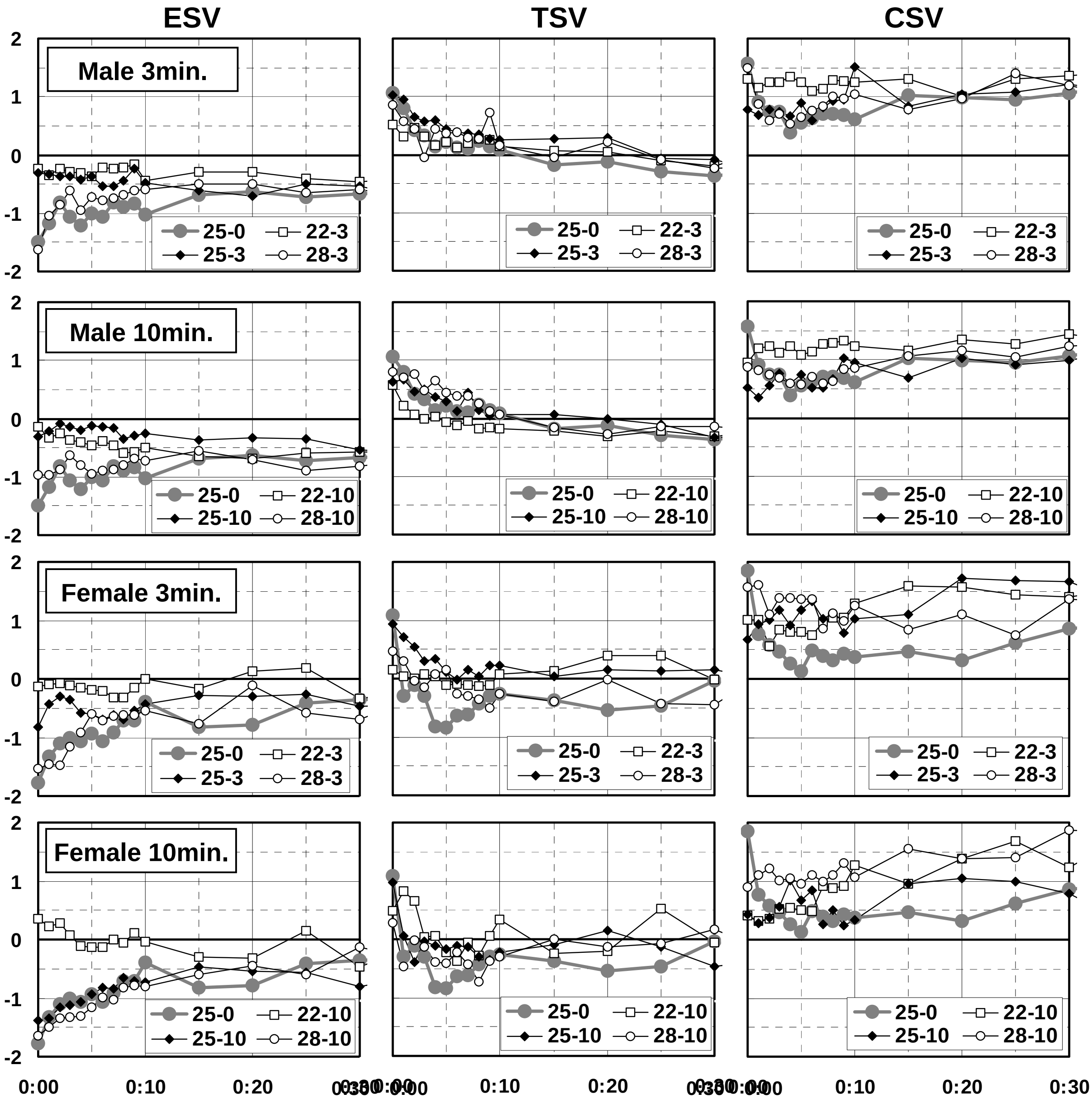


Figure 3-12. Variation of ESV, TSV, and CSV in post-transition indoor space

3.3.3.2 Physiological Variables

Figure 3-13 shows the deviation of mean skin temperature from the standard value and Figure 3-14 shows the vapor pressure variation inside clothing for 3 minute transition conditions. Results of the 10 minute transition condition are given in Figures 3-9 and 3-10.

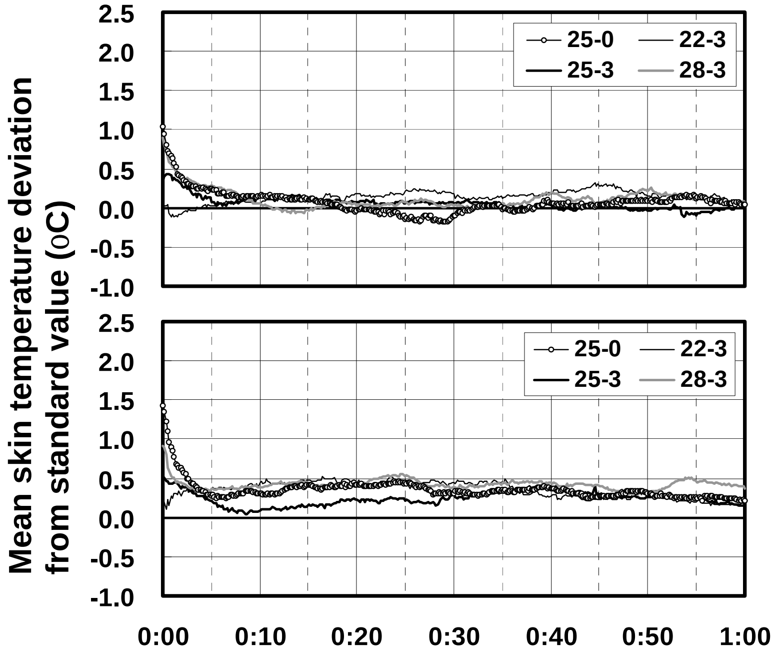


Figure 3-13. Mean skin temperature deviation from standard value (3 minute transition)

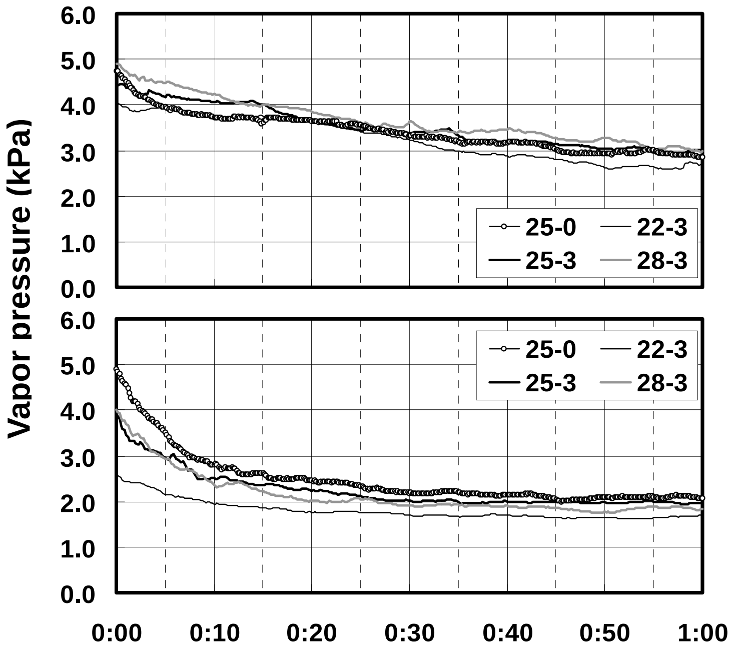


Figure 3-14. Vapor pressure variation inside clothing (3 minute transition)

1) Mean Skin Temperature:

The starting mean skin temperature was high in the order of 23-0, 28 °C conditions, 25 °C conditions, and 22 °C conditions, which was same as the order of preceding environment (32 °C for 23-0). The difference between conditions became larger when the transition time was longer, and the effect of buffer space condition was evident. Values of males and females reached a steady state value after 20 minutes for 3 minute transition conditions, but nearly 40 minutes were required for 10 minute conditions. Steady state mean skin temperature for 28-10 and 23-10 of males were about 0.5 °C lower than the pre-transition indoor space due to sweat accumulated in the undershirt which resulted in evaporative heat loss greater than under other conditions.

2) Vapor Pressure inside Clothing

Starting values were higher in the order of 28 °C, 25 °C, and 22 °C, but 23-0 was not the highest condition. Longer transition time within the same temperature condition resulted in higher vapor pressure. The total step exercise during the entire experimental process for 10 minute transition condition was 14 minutes longer than the 3 minute transition condition, and difference in accumulated amount of exercise may have affected the sweat rate before entering the post-transition indoor space. Vapor pressure of males were still in the process of decay at the end of experiment while females reached a steady state value for most of the conditions. The decay was quickest at 22 °C condition.

3.4 DISCUSSION

3.4.1 Environmental Temperature Sensation and Whole Body Thermal Sensation

Two separate thermal sensation scales, ESV and TSV, were introduced in the present experiment to avoid the confusion of two different concepts. ESV change was twice as large as TSV during transition phase, and ESV was significantly lower than TSV during occupancy phase. Subjects were able to distinguish the two different thermal sensation scales due to the fact that the two scales showed different characteristics. When evaluating thermal sensation during large environmental step changes, it is better to use two separate scales or to explain to the subjects clearly the difference between “sensation which describes the state of thermal environment” and “sensation which describes the thermal state of yourself” to avoid any confusion upon evaluation.

ESV variation and CSV variation during the environmental step change towards thermally neutral condition was found to correlate well, suggesting that ESV is an effective detector in evaluating the impression of the environment upon the step change.

3.4.2 Characteristic Difference Between Males and Females

In this experiment, both male and female subjects wore typical clothing ensembles for office work. The results showed the difference in physiological and psychological variables. Females were found to have larger step changes in sensation votes, and larger individual differences. The differences in clothing cannot explain all of the characteristic differences, but they need to be taken into consideration when specifying the optimum thermal condition for a buffer space.

3.4.3 Comfort Sensation

Kuno et al. (1987) indicated the presence of 2 different types of comfort, negative comfort and positive comfort (pleasantness). Negative comfort describes the state of no thermal strain, and positive comfort describes the state of mind accompanying the dismissal thermal strain. Gagge (1967) explained the manner of comfort sensation as anticipatory to physiological change during environmental step change towards thermally neutral condition by using the 4-point "discomfort" scale. Kuno et al. suggested that Gagge's interpretation of anticipation was a seeming description, which really is the positive comfort in earlier stage during relief from thermal strain gradually altering into negative comfort in the later stage.

A symmetrical 7-point "comfort" scale with "neutral" in the central category was used for the present experiment, and simple "anticipation" was not observed. During the environmental step change towards thermally neutral condition (25 °C), variation in ESV was associated with variation in CSV, which suggests that larger deviation from comfort leads to larger positive comfort. Several patterns of CSV variation in the comfort region above neutral was observed in the post-transition indoor space: 1) High upon entrance, sudden drop, and recovery, 2) low upon entrance and gradual recovery, 3) constant throughout at a certain level. It was difficult to assign the optimum CSV variation pattern for a given period of time from the present experiment, and further knowledge on positive comfort is required to determine the optimum CSV variation pattern.

3.4.4 Optimum Environmental Conditions of Buffer Space

Environmental condition of buffer space was found to have only minor influence on ESV, TSV, and CSV in post-transition indoor space after 40 minutes. This result corresponds to the result of Rohles et al. (1977), and environmental conditions of buffer space can be assumed irrelevant when evaluated for occupancy periods longer than 30 minutes.

Environmental condition of buffer space had a clear impact on physiological variables such as mean skin temperature and vapor pressure inside clothing. Mean skin temperature and vapor pressure inside clothing were higher when the air temperature of buffer space was higher and transition time was longer. Time required to reach steady state was also longer in post-transition indoor space. However, these influence were not prominent for psychological variables, and the only significant difference with no buffer condition (23-0) was found for ESV for the first vote upon entering post-transition indoor space. Related researches depicted in section 5.2 suggest that the transition from outdoor space through buffer space to indoor space is a transition towards thermally neutral condition, and that TSV leads the change in physiological variables. Simple anticipation was not observed for CSV due to the difference in comfort scale used, and several variation patterns were observed, though no significant difference from no buffer condition.

Optimum environmental condition may change depending on which period to be focused for the evaluation. The first 20 minutes after entrance especially requires further knowledge on positive comfort to determine the optimum environmental condition of buffer space.

3.5 CONCLUSION

Subjective experiments were conducted to investigate the effects of environmental conditions of the buffer space on thermal comfort in the succeeding environment, simulating a transition of an office worker from the office space to the outdoor space through the buffer space. Following conclusions were drawn.

1) Two separate scales of thermal sensation, environmental temperature sensation (ESV) and whole body thermal sensation (TSV), were used to distinguish the two different concepts of thermal sensation under transient conditions. Subjects were able to distinguish the two concepts owing to the fact that ESV and TSV showed different characteristics.
2) Variation in ESV was twice as large as TSV during the environmental step change. Variations in ESV and CSV correlated well during the environmental step change towards the thermally neutral condition. ESV was significantly lower than TSV by 0.3 - 0.4 scale units during the occupancy phase in the indoor space.
3) Sweat sensation and clothing acceptability was highly correlated with vapor pressure within clothing. Female responses for sweat sensation and clothing acceptability were more sensitive to a given vapor pressure than males.
4) Environmental conditions of the buffer space was found to have only minor influence on ESV, TSV, and CSV in the post-transition indoor space after 40 minutes. Environmental conditions of the buffer space were negligible when evaluated for occupancy periods longer than 30 minutes.
5) Environmental conditions of the buffer space had a clear impact on physiological variables such as mean skin temperature and vapor pressure inside clothing. Mean skin temperature and vapor pressure inside clothing were higher when the air temperature of the buffer space was higher and transition time was longer. Time required to reach steady state was also longer in post-transition indoor space.
6) The influence of environmental conditions of a buffer space was not prominent for psychological variables, and the only significant difference found with no buffer condition (23-0) was the first vote of ESV upon entering the post-transition indoor space.
7) Several fluctuation profiles were observed for comfort sensation votes after entering the

post-transition indoor space. Further investigation is required to specify the suitable profile for optimum thermal comfort conditions.

CHAPTER 4

DIFFERENCES IN PERCEPTION OF INDOOR ENVIRONMENT BETWEEN JAPANESE AND NON-JAPANESE WORKERS

CHAPTER 4 DIFFERENCES IN PERCEPTION OF INDOOR ENVIRONMENT BETWEEN JAPANESE AND NON-JAPANESE WORKERS

4.1 INTRODUCTION

The office is a place where the office workers spend most of their time, 10 hours per day on average according to the present survey, and have less control over their own environment. Therefore, a comfortable and healthy environment should be provided to this group in order for office workers to remain comfortable during their working day. When designing the environment, however, it should be taken into account that an optimum environment for one group of occupants may not be the optimum for all, and that such environments may become the cause of discomfort for other groups. The objective of this study is to investigate the differences in the way groups of occupants perceive the environment under real working conditions. Four seasonal surveys integrating physical measurements with questionnaires were conducted at an office building in Tokyo, Japan, where Japanese and non-Japanese occupants worked together on the same floor.

4.2 METHODS

Four seasonal surveys were carried out on 3 floors (I, II, III) of an office building located in Tokyo, Japan. The survey periods and corresponding outdoor conditions are presented in Table 4-1. The offices were located in the middle of a 37 story tenant building, consisting of a fully open plan office area of 1480 m^2 per floor subdivided by 1.1 m high private partitions. The offices were air conditioned with the centralized HVAC system of the building and additional supplementary cooling units. Office plan and cooling load for each zone are shown in Figure 4-1. The computer terminals were widely used throughout the space to produce heat and one of the floors, where difference in heat load distribution was the largest, was measured in detail. The floor was divided into 4 zones upon evaluation according to the arrangement of the workstations. The heat generating office equipment were clustered intensively at zone C, where a maximum use of 8 video display terminals per person was observed. Zone B had the second largest cooling load, and zone A and B were much less crowded compared to the others. The nationality of the workers was 60 % Japanese and 40 % non-Japanese, which is not so common in Japanese firms where most of the workers are usually Japanese. Majority of the Japanese workers and non-Japanese female workers were engaged in regular desk works while non-Japanese male workers mainly took part in an intensive trading business.

Table 4-1. Survey period and outdoor conditions

Season	Measurement period	Outdoor conditions*	
		Air temp. (℃)	Humidity (%rh)
Summer	Aug.13 - 15, 1997	24.8	71
Autumn	Oct.30 - 31, 1997	16.4	41
Winter	Jan.20 - 22, 1998	6.0	35
Spring	May.12 - 13, 1997	20.2	69

*Mean value of the survey period

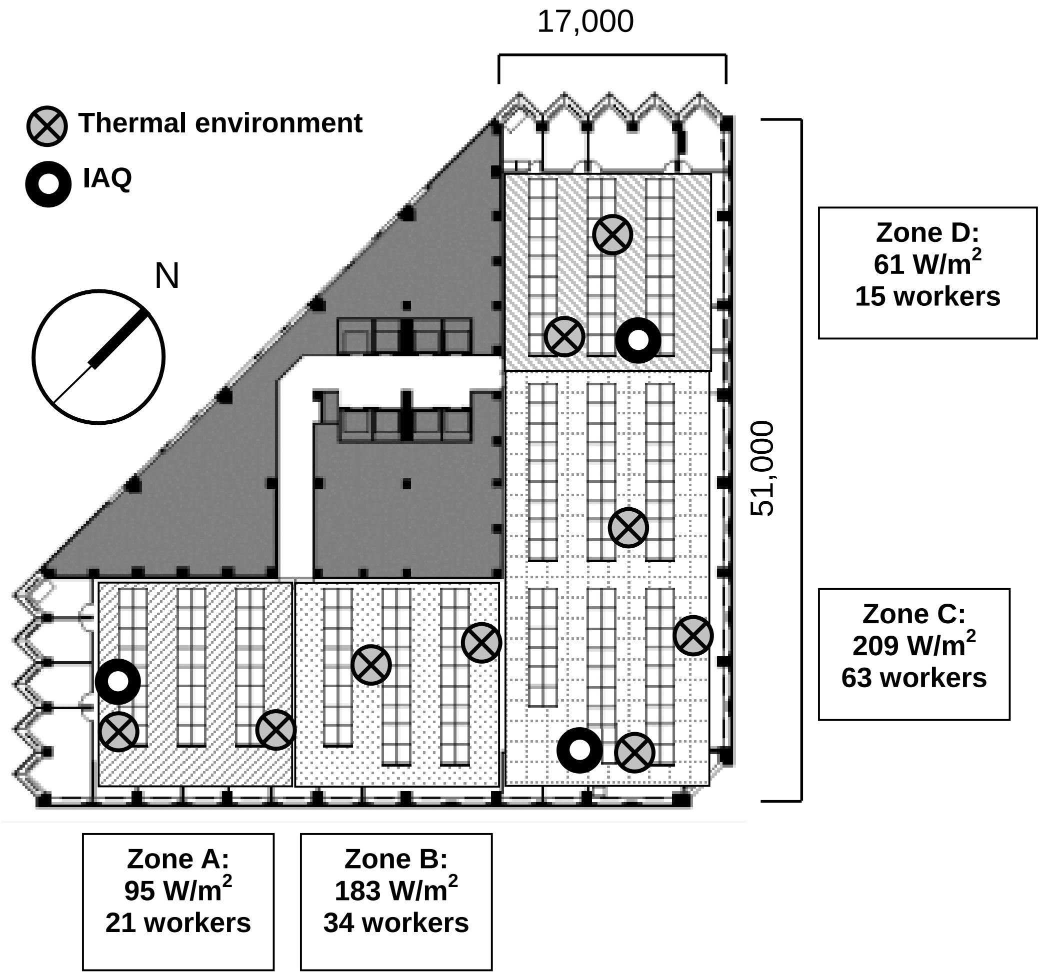


Figure 4-1. Office plan and measurement points

4.2.1 Thermal Environment Measurement

Spot measurements were conducted at representative points in the office area, five to ten per floor, utilizing a mobile instrumental cart. Measurement points of a representative floor are shown in Figure 4-1. The mobile measurement cart depicted in Figure 4-2 was utilized for spot measurements. The cart enabled a simultaneous evaluation of air temperature, globe temperature, air velocity, and relative humidity at 4 different heights as defined in ISO 7726 (1998) and ASHRAE 55-92 (1992). Measurement items, devices, and heights are given in Table 4-2. Diurnal fluctuations of air temperature and relative humidity were also recorded every five minutes for each floor during the survey period.

4.2.2 Indoor Air Quality Measurement

Concentrations of carbon dioxide (CO_2), carbon monoxide (CO), formaldehyde (HCHO), ozone (O_3), and suspended particles were measured at 1.1 m above floor level, two to four points per floor. Outdoor concentrations were also recorded at the end of every survey day. Diurnal fluctuations of CO_2 were also recorded on one of the floors.

4.2.3 Questionnaire Survey

The occupants were asked to assess their working environment for general comfort, thermal comfort, humidity sensation, and draft sensation. A part of questionnaire concerning comfort assessments is given in Figure 4-3. Unidirectional discomfort scale proposed by Gagge was used for comfort evaluation. Adding to the ASHRAE 7 point thermal sensation scale, McIntyre scale was used to assess thermal preference. The frequency of SBS related symptoms the occupants may have experienced at their working environment was also asked. Background information on sex, nationality, working hours, and the years they have stayed in Japan was also included. Questionnaires were handed out to all the occupants at the beginning of each survey, and were collected at the end of the survey. Analyses were made based on 406 questionnaires collected throughout the year.

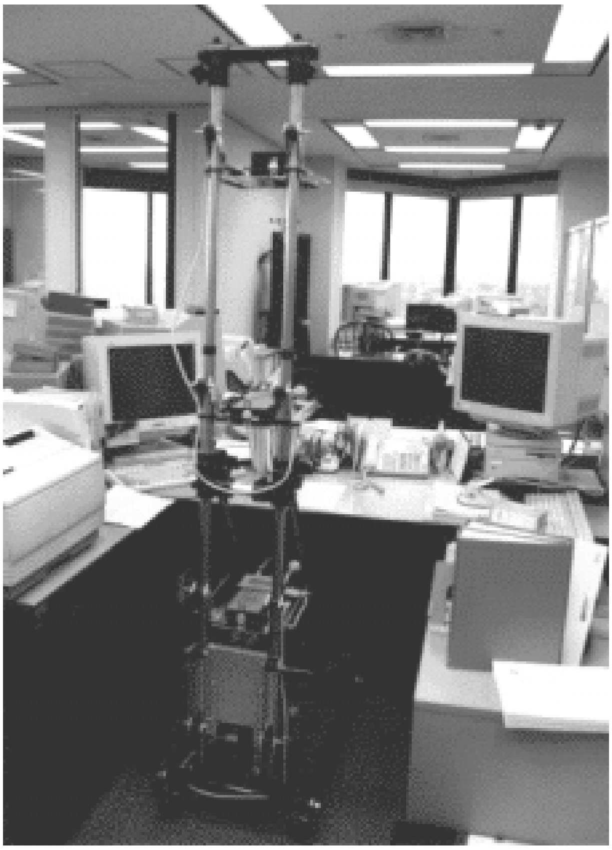


Figure 4-2. Measurement of workstation with mobile measurement cart

Table 4-2. Measurement item, device and height

	Measurement item	Measurement device	Height (m)
Thermal environment	Air temperature	C-C thermocouples	0.1 / 0.6 / 1.1 / 1.7
	Globe temperauture	Small globe	0.1 / 0.6 / 1.1 / 1.7
	Plane radiant temperature	B&K1213	1.1 / 6 sides
	Air velocity	B&K1213	0.1 / 0.6 / 1.1 / 1.7
	Relative humidity	TDK RH sensor	1.1
Indoor air quality	Carbon dioxide	CO_2 detector	1.1
	Carbon monoxide	CO detector	1.1
	Suspended particles	Shibata P5 H-2	1.1
	Formaldehyde	HCHO detector	1.1
	Ozone	O_3 detector	1.1

Q12. Please complete each of the following statements by checking the box that best expresses your personal feelings or preferences.

1) On average, I perceive my work area to be: (check one)
- ☐ comfortable
- ☐ slightly uncomfortable
- ☐ uncomfortable
- ☐ very uncomfortable

2) On average, I perceive the TEMPERATURE of my work area to be:
(disregarding the effects of air movement, lighting and humidity)
- ☐ hot
- ☐ warm
- ☐ slightly warm
- ☐ neutral
- ☐ slightly cool
- ☐ cool
- ☐ cold

3) How do you prefer the temperature to be?
- ☐ warmer
- ☐ no change
- ☐ cooler

4) Do you feel any AIR MOVEMENT in the work area?
☐ Yes ☐No

5) If yes, do you find the AIR MOVEMENT uncomfortable?
☐ Yes ☐No

6) On average, I perceive the HUMIDITY of my work area to be:
(disregarding the effects of temperature, air movement and lighting)
- ☐ very humid
- ☐ slightly humid
- ☐ neutral
- ☐ slightly dry
- ☐ very dry

Q13. Below are some symptoms that people experience at different times. Please indicate how often YOU HAVE EXPERIENCED EACH SYMPTOM IN THE PAST MONTH by circling the appropriate number from the scale below. (Please circle one number for each symptom)

	Never		Very often		
a) Headache..	1	2	3	4	5
b) Dizziness	1	2	3	4	5
c) Sleepiness...	1	2	3	4	5
d) Sore or irritated throat..	1	2	3	4	5
e) Nose irritation (itch or running)...........................	1	2	3	4	5
f) Eye irritation...	1	2	3	4	5
g) Trouble focusing eyes...	1	2	3	4	5
h) Difficulty concentrating.......................................	1	2	3	4	5
i) Skin dryness...	1	2	3	4	5
j) Skin rash or itch...	1	2	3	4	5
k) Fatigue..	1	2	3	4	5
l) Unpleasant Odor..	1	2	3	4	5

Figure 4-3. Questionnaire sheet

4.3 RESULTS OF PHYSICAL MEASUREMENTS

4.3.1 Thermal Environment

Indoor air temperature and humidity observations are plotted against outdoor condition at the time of measurement in Figure 4-4. The indoor temperature was controlled throughout the year, irrespective of the outdoor temperature. Indoor humidity was mainly controlled in between 5 to 10 g/kg, although a slight influence of outdoor conditions was confirmed. Mean air temperature profiles of each zone on the floor are plotted in Figure 4-5 for each season. Temperatures were inconsistent throughout the year, and showed no relationship with the outdoor conditions. Though vertical temperature difference was within 1.5 °C, horizontal temperature difference of more than 2.5 °C was observed throughout all seasons, with the maximum difference of 4.6 °C in spring. The only exception appeared in autumn. The office environment was controlled with the centralized HVAC system of the building, called the landlord system, and additional cooling units, called the tenant system. The landlord system was set to control the air temperature at 23 °C, while set point of the tenant system, divided into 8 independent control areas, was allowed for free access of occupants until summer. This resulted in creating uneven distribution and fluctuation of air temperature as shown in Figure 4-6, since occupants feeling cold and those feeling hot kept turning on or off the air conditioning. The controllers were disabled after summer, and corporate service manager altered the settings at the request of the occupants. In winter and spring, some of the areas were heated while others were cooled, causing large horizontal differences and fluctuation. The differences in air temperature and globe temperature were less than 1.0 °C. Air velocities were mostly below 0.25 m/s in the occupied area, except that some occupants near the outlet grills reported their environment to be drafty. Though the relative humidity was kept around 50 % in summer and spring, the values were lower in autumn and winter, with the minimum of 24 % rh in winter. The cause was found in the air conditioning system, where landlord system introduced mixed air of indoor and outdoor, while the tenant system used recirculated air only. The ratio of outdoor air was increased in cool seasons and decreased in warm seasons from energy conservation point of view. As shown in Figure 4-7, mean indoor humidity had the same tendency as the outdoor humidity. The air was dehumidified in summer and spring, but not so much humidification was made in autumn and winter.

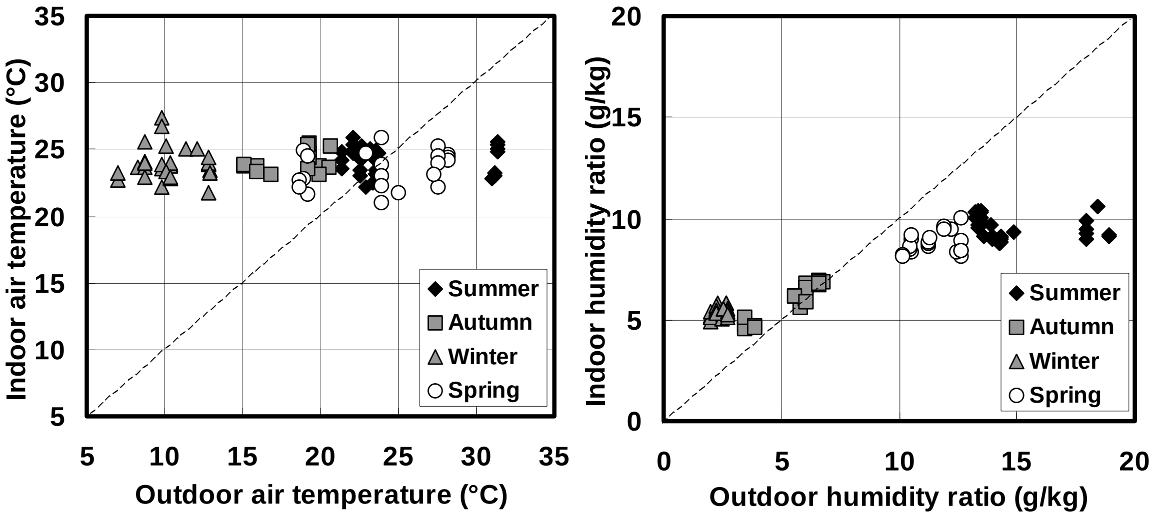


Figure 4-4. Indoor air temperature and humidity ratio in relation to outdoor conditions

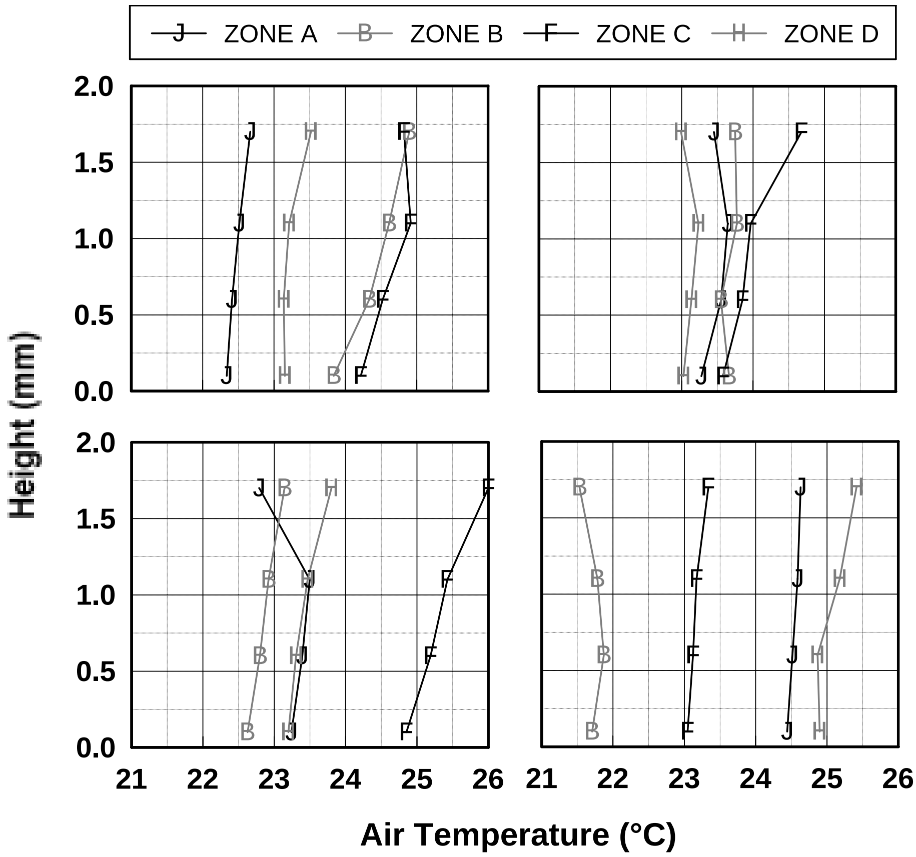


Figure 4-5. Vertical air temperature profiles for each zone

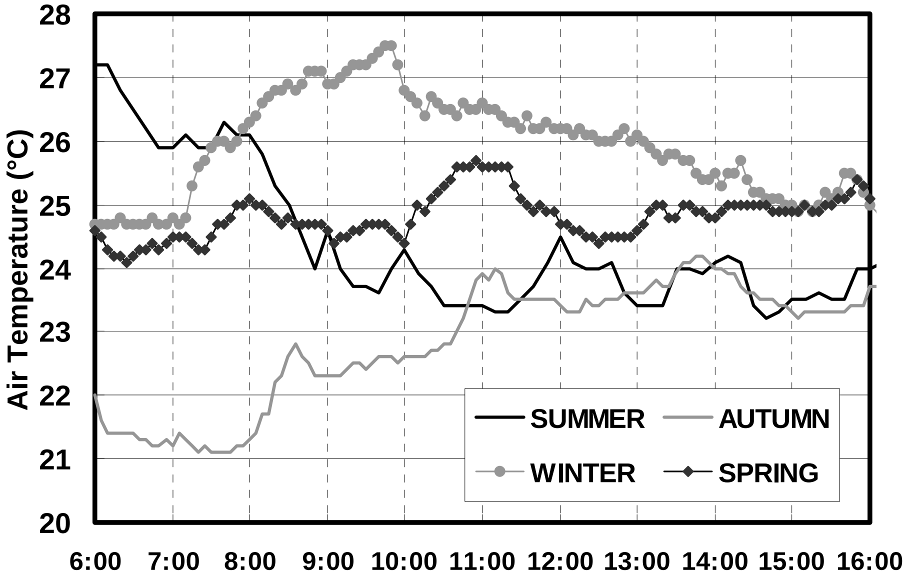


Figure 4-6. Diurnal air temperature fluctuation

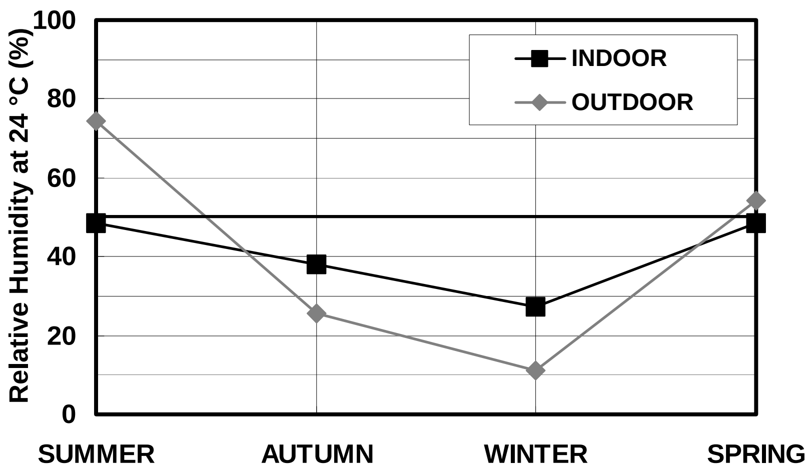


Figure 4-7. Seasonal variation of indoor and outdoor relative humidity converted at 24 °C

4.3.2 Indoor Air Quality

Diurnal fluctuation of CO_2 concentration is shown in Figure 4-8. Due to malfunctions of the measurement device, data on winter were not recorded. Overall concentration was rather high in summer and spring, exceeding the limit of 1000 ppm defined in the Law for Maintenance of Sanitation in Buildings, Japan, while the values were much lower in autumn. Sudden rise at 18:00 was also significant. As mentioned in the earlier section, landlord system introduced mixed air, and the tenant system used recirculated air only. When the landlord system was shut down at 18:00, the supply of fresh air was also cut, resulting in a sudden rise of CO_2 concentration. The peaks were observed at around 19:00, when many occupants were still working. The ratio of outdoor air was increased in cool seasons, and CO_2 concentration was kept lower in autumn compared to other seasons. Formaldehyde concentration did not correspond with the seasonal difference of fresh air introduction, as presented in Figure 4-9. On one of the floors, mean value of formaldehyde concentration exceeded the WHO limit (1987) of 0.08 ppm in spring. Renewal of some of the furniture took place in spring, and the concentration was generally higher compared to other seasons. General guidelines on VOC emission of materials has not been issued in Japan, and some of the newly installed furniture still emit high concentration of VOCs. Smoking was not allowed in the office spaces, and CO concentration was kept below 2 ppm. The detector with the minimum range of 0.025 ppm could not detect ozone throughout the year. Suspended particles were also low, 0.015 mg/m3 at the highest in spring.

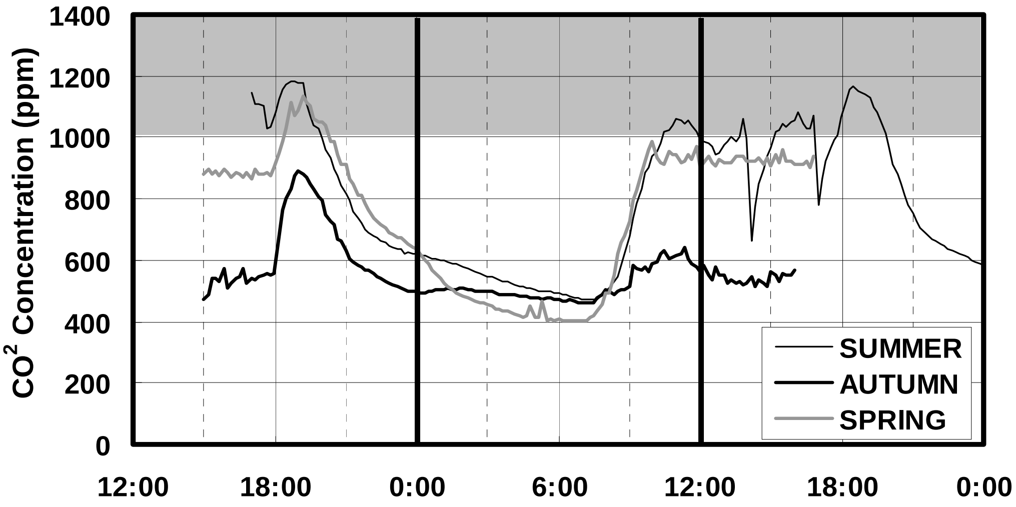


Figure 4-8. Diurnal carbon dioxide concentration fluctuation of floor “ I ”

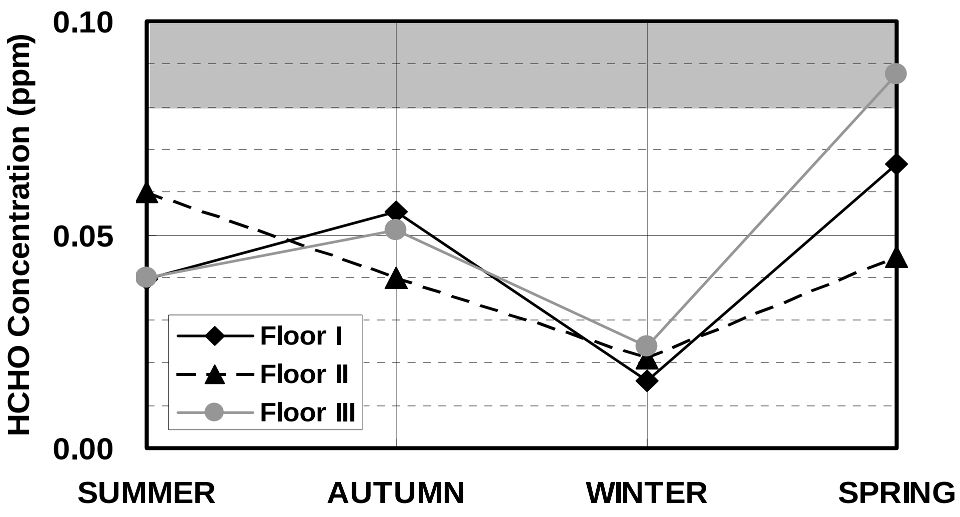


Figure 4-9. Seasonal variation in formaldehyde concentration

4.4 RESULTS OF QUESTIONNAIRE SURVEY

4.4.1 Thermal Sensation

Of all the 406 returned questionnaires throughout the year, only 26 % rated their working environment to be "comfortable". As shown in Figure 4-10, comfort votes showed a good correlation with the thermal sensation votes. Because the percentage of occupants who voted their thermal environment to be "neutral" was also low indicating only 26 %, individual differences in thermal preference were suspected to be the cause of low comfort ratings. The relationship between operative temperature and mean thermal sensation vote was sought among several groups of occupants. The occupants were grouped into male, female, Japanese, and non-Japanese. Among the non-Japanese nationalities were 35 % North Americans, 26 % Europeans, 22 % Asians other than Japanese, and 17 % others. The average years the non-Japanese workers have stayed in Japan were 4.7 years (SD=5.5), and 61 % of them have stayed in Japan for less than 5 years. Since 88 % of the workers were in their twenties and thirties, age groups were not considered. The number of replies for each group is given in Table 4-3. The non-Japanese female group was omitted from an independent group analysis due to small number of replies. The thermal environment of each occupant was assigned according to the nearest measurement point of that season, and mean operative temperature of the seasonal measurement was used to represent the value of the specific location. The mean operative temperatures were binned into 0.5 °C increments, and corresponding thermal sensation votes were used for analysis. Weighted linear regression analysis was applied to each group and the neutral temperature for the mean thermal sensation vote of 0 was calculated. The results are presented in Table 4-3 and Figure 4-11. The size of the plot in the figure represents the number of replies. Significant differences in neutral temperature were found between occupant groups of "Japanese male - Non-Japanese males" ($p<0.01$), "Japanese females - Non-Japanese males" ($p<0.01$), and "Japanese females - Japanese males" ($p<0.05$). The largest difference was observed between Japanese females and non-Japanese males, reaching 3.1°C. These results suggest the presence of diverse neutral temperatures among individual occupants working in the same area, causing difficulties in realizing a thermally comfortable environment for everybody simultaneously.

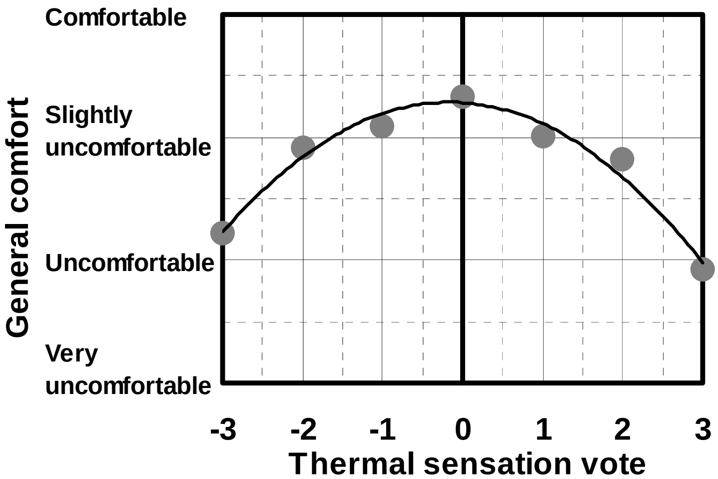


Figure 4-10. Thermal sensation votes and corresponding mean comfort votes

Table 4-3. Number of returned questionnaires and neutral temperature for each occupant group

	Male	Female	Total
Japanese	n=97	n=161	n=258
neutral temperature (°C)	24.3	25.2	24.8
Non-Japanese	n=125	n=23	n=148
neutral temperature (°C)	22.1	--	22.7
Total	n=222	n=184	n=406
neutral temperature (°C)	22.9	25.1	23.9

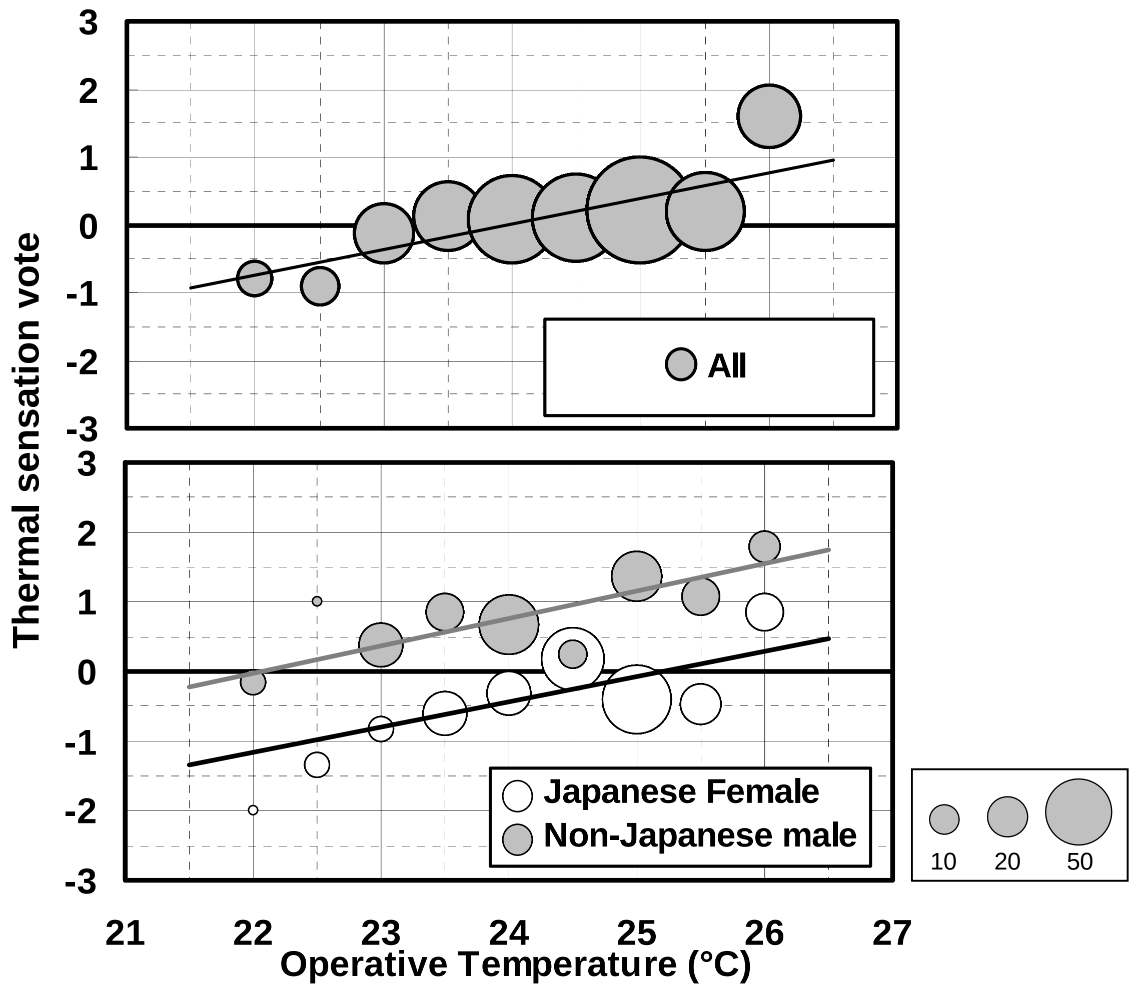


Figure 4-11. Operative temperature and corresponding thermal sensation votes

4.4.2 Humidity Sensation

Using the same method as above, relative humidity was binned into 5 % increments and assigned to each occupant. Corresponding humidity sensation votes were used for analysis. The results are presented in Figure 4-12. Mean humidity sensation of all occupants showed neutrality at 55 %rh. The Japanese females reported more dryness compared to non-Japanese males under 55 %rh. Mean votes of the non-Japanese males showed a value close to "neutral" in the range of 25 - 60 %rh.

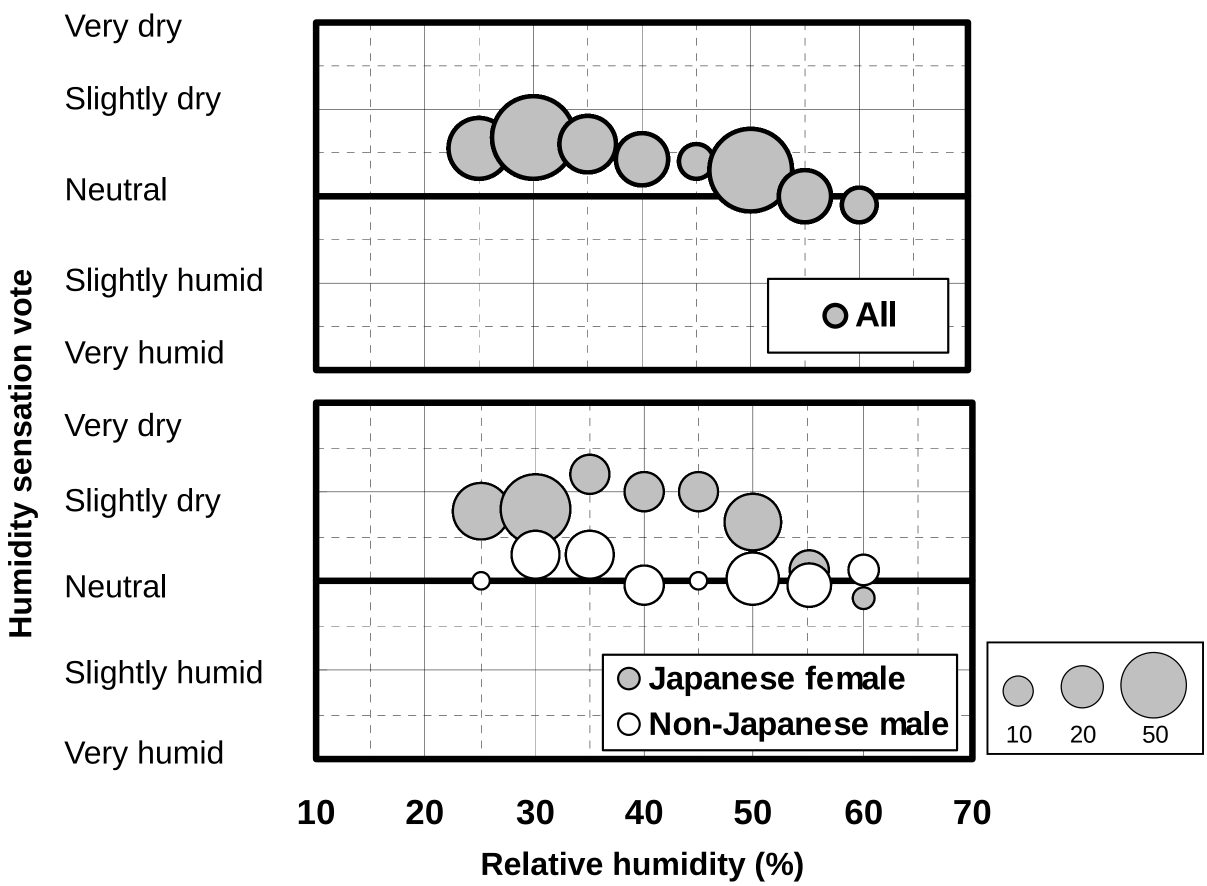


Figure 4-12. Relative humidity and humidity sensation vote

4.4.3 Frequency of SBS Related Symptoms

The five-point frequency scale used in the questionnaire was converted to a relative frequency scale of 0 - 1.0 upon analysis. The relative frequencies of SBS related symptoms for each group of occupants are shown in Figure 4-13. Of the three groups, Japanese females reported the highest frequency of symptoms. The Japanese female group reported higher frequency of physical symptoms such as “eye irritation” and “skin dryness”, while male occupant groups reported more mental symptoms such as “sleepiness” or “fatigue”.

A poor correlation was found between the frequency of SBS symptoms and CO_2, CO, and HCHO concentrations inside the office. Significant correlations ($p<0.01$) were found with relative humidity for symptoms such as “eye irritation”, “sore or irritated throat”, and “skin dryness”. The results are shown in figure 4-14.

A higher correlation was found with thermal sensation votes rather than with the physical state of the environment. Individual symptoms such as “headache” and “fatigue” showed a close relationship as well as the average frequency of all symptoms, as presented in Figure 4-14.

The correlation of comfort votes and thermal sensation votes was mentioned in the earlier section, but a strong correlation between comfort votes and average frequency of SBS symptoms was also observed. Figure 4-15 shows the drop in comfort scales corresponding to the increase in relative frequency.

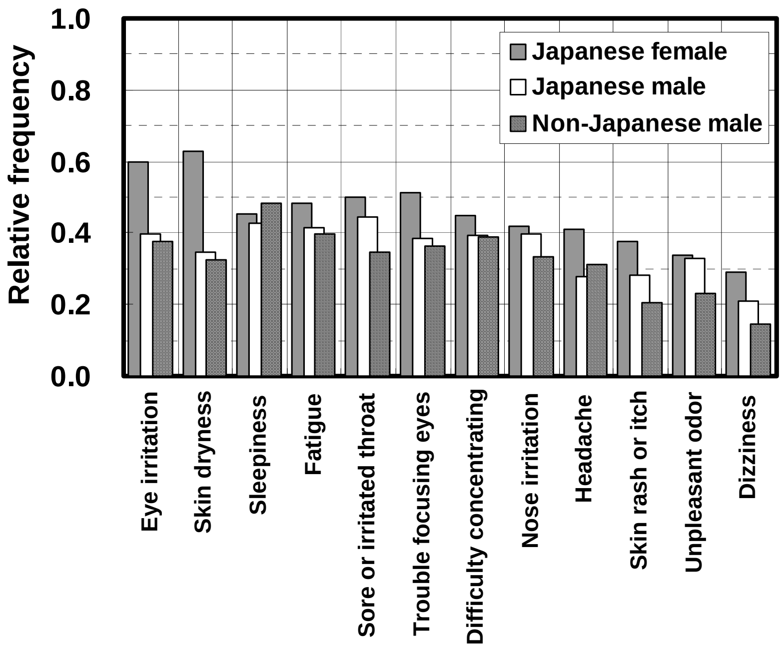


Figure -13. Relative frequency of SBS related symptoms for 3 occupant groups

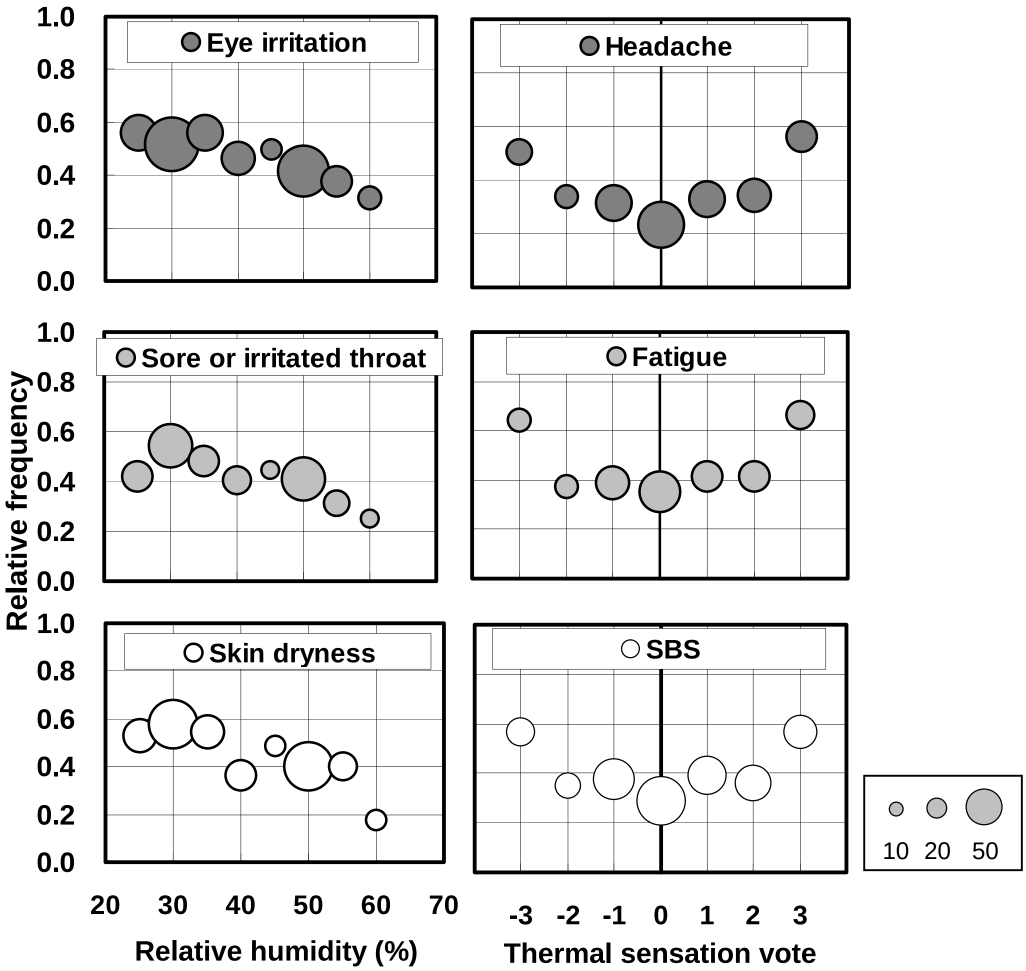


Figure 4-14. Relative frequency of SBS related symptoms against relative humidity and thermal sensation vote

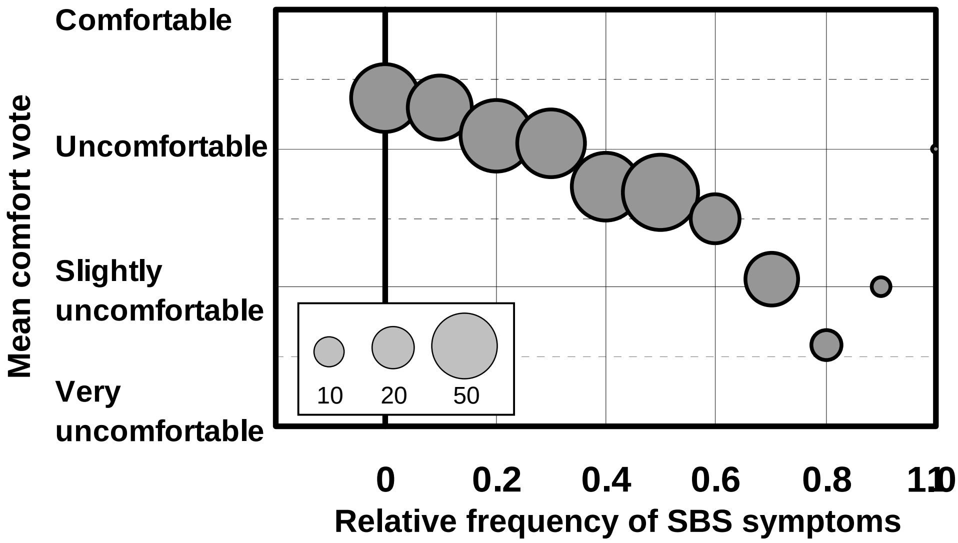


Figure 4-15. Relative frequency of SBS related symptoms and mean comfort vote

4.5 DISCUSSION

4.5.1 Neutral Temperature

As a result of extensive subjective experiments conducted in the climate chamber, Fanger (1970) concluded that age, sex, and national- geographic differences did not influence the neutral temperature of the subjects. Laboratory tests conducted by Tanabe et al. (1994) and de Dear et al. (1991a) (1991b) also showed that there was no significant difference in thermal neutrality between Caucasian and Japanese. However, from the analysis of the current survey, a neutral temperature difference of 3.1°C was observed among the Japanese females and non-Japanese males. Though the classification of nationality may be questioned, the Japanese was a dominant group of the occupants and other nationalities could not be classified into smaller groups. Three factors are considered as the cause of difference in neutral temperature: clothing, type of work, and expectation.

1) Clothing: Present survey was conducted during the working hours. Because the number of questions was limited on a questionnaire, detailed survey on clothing could not be conducted. Although clothing of male and female occupant groups was visually confirmed to be different, male occupant groups all wore business suits. Clothing alone is unlikely to be the sole factor causing the large difference in thermal sensation within the male group.

2) Type of work: As opposed to most of the Japanese male and female workers who were engaged in regular desk works, non-Japanese male workers mainly took part in an intensive trading work. The latter type of work forces mental stress during the working hours, and bodily movements resulting from stress or stress itself might have well influenced the perception of thermal environment. Little work has been done on thermal comfort under conditions of mental stress, and the degree of its influence was not clear here.

3) Expectation: Environments deviating from expectations are likely to result in discomfort. According to a series of office surveys conducted from 1995 to 1998 in Japan, the yearly average office temperature was found to be 24.5 – 25.0 °C (SHASE, 1993). This value is quite close to neutral temperature of 24.8 °C found for Japanese occupants. Also, on the basis of extensive office surveys conducted mainly in the US and Australia, de Dear et al. (1998) proposed the optimum indoor operative temperature of buildings with centralized HVAC to be 23.5°C in summer and 22.5°C in winter. The neutral temperature for the non-Japanese occupant group was found to be 22.7°C, falling within the 90 % acceptability operative temperature range for both summer and winter. These facts suggest that the neutral temperatures found for each of the groups are reasonable, and that the air temperature settings the occupants are accustomed to may have influenced the degree of expectation for the office environment.

The present study was based on a field survey, and measurement items were limited. Although the factors resulting in the neutral temperature difference could not be specified from the present survey, the existence of diverse neutral temperatures was confirmed under usual working conditions. These occupants working together in the same room is supposed to have led to the low thermal comfort ratings in the present office.

4.5.2 Frequency of SBS Related Symptoms

Frequency of SBS related symptoms overall was found to be more highly correlated with the thermal sensation votes, rather than the physical state of the environment. Jaakkola et al. (1989) reported that an indoor temperature rise from 22°C resulted in the rise of SBS related symptoms. However, this was because the perception of the thermal environment was similar among the occupants. As can be seen from the results of the present survey where significant differences in neutral temperature were confirmed between the groups, SBS related symptoms are more related to their thermal sensation votes rather than the temperature itself. The report of the high frequency of SBS related symptoms could be considered to be an indication of dissatisfaction for the given environment.

Comfort votes were confirmed to drop as the relative frequency of symptoms rose. By observing the overall results of the questionnaire survey, it was concluded that the main factor causing dissatisfaction in the present office was the thermal environment, which consequently influenced the ratings on the frequency of SBS related symptoms and general comfort in the working environment

4.6 CONCLUSION

Field surveys were conducted at an office with Japanese and non-Japanese workers to investigate the differences in the way groups of occupants perceive the environment under real working conditions. Returned questionnaires were divided into 3 groups according to their nationality and sex. The results are summarized as follows.

1) Only 26% of workers reported their working environment to be “comfortable”. At the same time, only 26% voted their thermal environment to be “neutral”.
2) A significant neutral temperature difference of 3.1 °C was observed between the Japanese female occupant group and the non-Japanese male group.
3) Japanese female occupants felt the air to be dry below 55 %rh, while male occupants were less sensitive to low humidity.
4) Japanese female groups reported a higher frequency of SBS related symptoms compared to the other occupant groups. Male groups tended to report mental symptoms such as "sleepiness" and "fatigue", while females reported more physical symptoms such as "skin dryness" and "eye irritation".
5) The comfort votes and the reported frequency of SBS related symptoms were closely related to the deviation of thermal sensation vote from neutral.
6) The thermal environment was found to be the major factor affecting occupant comfort in the particular office.
7) Occupants in the present office were relying on the adjustment of thermal environment to achieve comfort, and the differences in the perception of the indoor environment were negatively affecting the ratings of their working environment. The results indicate the importance of personal adaptation such as clothing adjustment to achieve comfort even in the air-conditioned indoor environment.

CHAPTER 5

THERMAL COMFORT CONDITION IN SEMI-OUTDOOR ENVIRONMENT FOR SHORT-TERM OCCUPANCY

CHAPTER 5 THERMAL COMFORT CONDITION IN SEMI-OUTDOOR ENVIRONMENT FOR SHORT-TERM OCCUPANCY

5.1 INTRODUCTION

The term "semi-outdoor space" refers to an architectural environment where outdoor elements are designedly introduced with the aid of environmental control. The level of control in semi-outdoor environment may range from simple shading and wind shielding in an open structured terrace to mechanical heating, cooling, and ventilation in a closed glazing structure of an atrium. These spaces such as an atrium or terrace are designed often from an aesthetic point of view or to add diversity to the architectural environments. However, main use is usually not for long-term occupancy lasting for hours, and tight control of thermal environment by the HVAC system as described in existing indoor thermal comfort standards may not be required. Although little work has been done on thermal comfort in semi-outdoor environments, it is likely that people expect circumstances differing from indoors, and the thermal comfort condition in terms of short-term occupancy may differ from that of indoor steady state.

The purpose of this study is to investigate the actual occupancy condition, thermal adaptation process and thermal comfort condition in relation to the level of environmental control applied. A series of seasonal field surveys was designed and carried out in four semi-outdoor architectural environments from the summer of 2001 to spring of 2002.

5.2 METHODS

5.2.1 Survey Area

Four semi-outdoor architectural environments with different levels of environmental control were selected for the survey in Tokyo, Japan, two of which were air-conditioned atria and two of which were non-air conditioned spaces. Buildings were selected to have a common basic feature; large-scale precincts open to public, designed for roaming and resting of the visitors. The details of the selected environments are listed in Table 5-1.

Table 5-1. Description of the survey areas

					
Building	O		T	P	B
Location	N 35º 40' E 139º 41'		N 35º 41' E 139º 42'	N 35º 40' E 139º 41'	N 35º 35' E 139º 44'
Description	office + shopping mall		departmenmt store	office + shopping mall	office + shopping mall
Survey area	arcade	sunken garden	wooden deck	closed atrium	closed atrium
Dimension (floor area * height)	830 m^2 x 16 m	650 m^2 (no roof)	1,500 m^2 (no roof)	1,600 m^2 × 18 m	4,200 m^2 × 40 m
HVAC	non		non	all year	all year

5.2.2 Survey Period

Japan has a distinctive seasonal climate, and influence of seasonal change is expected to be large on thermal condition of semi-outdoor environments. In order to examine the seasonal average characteristic independent of hourly or daily changes of occupancy condition, surveys were conducted from 10:00 to 18:00 for four weekdays per building per season for four seasons. The survey periods, a total of 64 days, are given in Table 5-2. All surveys were conducted regardless of the weather conditions except for Building T where major part of survey area was uncovered, and visitors were unable to occupy the area due to wet furniture.

Table 5-2. Survey periods

Building	Summer		Autumn		Winter		Spring	
O	Aug.	20, 21	Oct.	15, 16	Dec.	10, 11	Apr.	8, 9
		24, 25		18, 19		13, 14		11, 12
P	Aug.	27, 28	Oct.	22, 23	Jan.	11, 15	Apr.	22, 23
	Sep.	3, 4		25, 26		17, 18		25, 26
T	Sep.	6, 7	Oct.	30, 31	Jan.	29, 31	Apr.	15, 16
		26, 27	Nov.	6, 19	Feb.	1, 4		18, 19
B	Sep.	13, 14	Nov.	12, 13	Jan.	21, 22	May	13, 14
		18, 19		15, 16		24, 25		16, 17

5.2.3 Survey Design

Three survey methods were integrated into the survey design: 1) investigation of the occupancy condition, 2) questionnaire survey and 3) measurement of the thermal environment. The present survey was focused on “short-term occupants” defined as the visitor who actually sat down in the survey area, and a passer-by or a standing person was left out of scope.

For the first objective, occupancy period was measured throughout the day by randomly selecting the visitors upon sitting in the area and recording the time of arrival and departure. The number of occupants within the survey area was also counted every ten minutes. Questions concerning the background information, purpose of stay and frequency of visit were included in the questionnaire.

Questionnaire sheet written in plain Japanese also included questions concerning approximate length of stay, activity within 15 minutes, clothing items, general comfort, thermal sensation, thermal preference, and thermal acceptability. In order to avoid any apparent errors, a surveyor also recorded the basic background information and clothing items of the respondent that could be confirmed visually. Questionnaire sheet translated into English is presented in Figures 5-1 and 5-2.

A mobile measurement cart was devised to measure the thermal environment around the occupants at heights of 0.1, 0.6, 1.1, 1.7 m above ground. Measurement items are given in Table 5-3. The radiant environment was evaluated by measuring the directional total radiation and solar radiation separately for six directions (up, down, front, back, left, right) at 1.1m above floor level. Orientation of the sensors was also recorded. Outdoor conditions were recorded separately.

After earning the consent of an occupant to answer the questionnaire, another surveyor drove the cart near the respondent to measure the surrounding environment for ten minutes as depicted in Figure 5-4. Five minute average prior to the end of each measurement was regarded as the representative value of thermal environment for that respondent. A total of 2248 occupant responses and corresponding sets of thermal environment data were collected throughout the four seasonal surveys. The collected number for each building and season is presented in Table 5-4. Surveys were carried out with 4 personnel each day.

Thermal Comfort Questionnaire

Survey Number____________

Dept. of Architecture, WASEDA University.

Please write in or mark a check on the box.

① **What is your <u>sex</u> and <u>age</u>?**

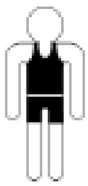
☐Male ☐Female

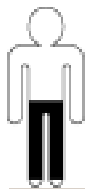
☐ < 20 ☐20-29 ☐30-39 ☐40-49 ☐50-59 ☐60-69 ☐ 70 <

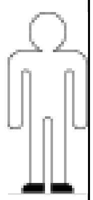
② **What is your <u>occupation</u>?**

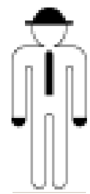
☐Business man / woman ☐Housewife ☐Part timer ☐Student ☐Others ( )

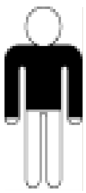
③ **Please check the <u>clothing items</u> you are wearing <u>at this moment</u>.**

Under	Item	Sleeve: Long	Short	None
	☐Top wear	[☐	☐	☐]
	☐Socks			
	☐Stocking			
	☐Tights	Short	Knee	Ankle
	☐Bottom wear	[☐	☐	☐]

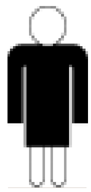
Bottom	Item			
	Pants / Trousers	Lite	Heavy	
		[☐	☐]	
		Short	Knee	Ankle
		[☐	☐	☐]
	Skirt	Lite	Heavy	
		[☐	☐]	
		Short	Knee	Ankle
		[☐	☐	☐]

Shoes	Item
	☐Leather shoe
	☐Gym shoes
	☐Sandals
	☐Short boots
	☐Long boots

Others	Item
	☐Necktie
	☐Hat/cap
	☐Muffler
	☐Shawl
	☐Scarf
	☐Gloves
	☐Ear pads

Top	Item	Long	Short	None	Lite	Heavy
	Button-down (Y shirt / blouse)	[☐	☐	☐]	[☐	☐]
	Shirt (Tshirt / Polo shirt)	[☐	☐	☐]	[☐	☐]
	Other shirt (Turtle neck, etc.)	[☐	☐	☐]	[☐	☐]
	One-piece	[☐	☐	☐]	[☐	☐]

Item	Short	Knee	Ankle	Lite	Heavy
Vest	[☐	☐	☐]	[☐	☐]
Sweater	[☐	☐	☐]	[☐	☐]
Sweat shirt (Fleece, etc.)	[☐	☐	☐]	[☐	☐]
Cardigan	[☐	☐	☐]	[☐	☐]
Turtle neck sweater	[☐	☐	☐]	[☐	☐]
Jacket	[☐	☐	☐]	[☐	☐]

Coat	Item	Lite	Heavy
	Long coat	[☐	☐]
	Half coat	[☐	☐]
	Leather jacket	[☐	☐]
	Windbreaker	[☐	☐]
	Down jacket	[☐	☐]
	Trench coat	[☐	☐]

④ **What is the <u>purpose</u> of your stay here?**

☐Resting ☐Meal ☐Waiting ☐Reading ☐Computer ☐Smoking ☐Mobile phone ☐Others (_________)

⑤ **Are you <u>sweating</u> right now?**

☐Not sweating ☐Slightly sweating ☐Sweating ☐Very much sweating

⑥ **<u>How long</u> have you been here?**

☐ < 5 min. ☐5-10 min. ☐10-15 min. ☐15 min. <

⑦ **What were you doing <u>just before this survey</u>?**

☐Resting ☐Meal ☐Waiting ☐Reading ☐Computer ☐Smoking ☐Mobile phone ☐Others (_________)

⑧ **What were you doing <u>15 minutes ago</u>?**

☐Indoor work ☐Outdoor work ☐Meal ☐Shopping ☐Walking

☐Exercise ☐Staying here ☐Moving by foot ☐Moving by transportation ☐Others (_________)

⑨ **How is your <u>health condition</u> today?**

☐Good ☐Fair ☐Not good ☐Bad

⑩ **Have you drunk any <u>alcoholic beverage</u> in the <u>past two hours</u>?**

☐Yes ☐No

⑪ **Do you know the <u>weather forecast</u> for today?**

☐Yes ☐No

⑫ **How many times have you <u>visited this place in the past</u>?**

☐0 ☐ < 5 ☐ < 10 ☐ 11 <

Figure 5-2. Questionnaire sheet (front)

Please answer the questions below with regard to <u>the environment you are sitting right now</u>.

⑬-1 How comfortable is the present environment?

☐ Very Comfortable	☐ Comfortable	☐ Slightly Comfortable	☐ Neutral	☐ Slightly Uncomfortable	☐ Uncomfortable	☐ Very Uncomfortable
+3	+2	+1	0	-1	-2	-3

⑬-2 If you answered "Very comfortable", "Comfortable", or "Slightly comfortable" on question ⑬-1, what elements below contributed to your comfort? (multiple answers)

☐Temperature ☐Humidity ☐Sunlight ☐Wind ☐Sound ☐Smell ☐Vegetation ☐Furniture ☐Openness
☐Spaciousness ☐Brightness ☐Smoking ☐Presence of others ☐Others (________________)

⑬-3 If you answered "Very uncomfortable", "Uncomfortable", or "Slightly uncomfortable" on question ⑬-1, what elements below contributed to your discomfort? (multiple answers)

☐Temperature ☐Humidity ☐Sunlight ☐Wind ☐Sound ☐Smell ☐Vegetation ☐Furniture ☐Openness
☐Spaciousness ☐Brightness ☐Smoking ☐Presence of others ☐Others (________________)

⑭ How do you feel the present environment to be?

☐Hot	☐Warm	☐Slighlt warm	☐Neutral	☐Slightly cool	☐Cool	☐Cold
+3	+2	+1	0	-1	-2	-3

⑮ How do you want the <u>temperature</u> to be?

☐Warmer ☐No change ☐Cooler

⑯-1 Do you feel any <u>air movement</u>?

☐Yes ☐No

⑯-2 How do you want the <u>air movement</u> to be?

☐Stronger ☐No change ☐Weaker

⑰-1 How do you feel the <u>humidity</u> to be?

☐Very humid ☐Humid ☐Neutral ☐Dry ☐Very dry

⑰-2 How do you want the <u>humidity</u> to be?

☐Higher ☐No change ☐Weaker

⑱-1 Do you feel the <u>direct solar radiation</u>?

☐Yes ☐No

⑱-2 How do you want the <u>solar radiation</u> to be?

☐Stronger ☐No change ☐Weaker

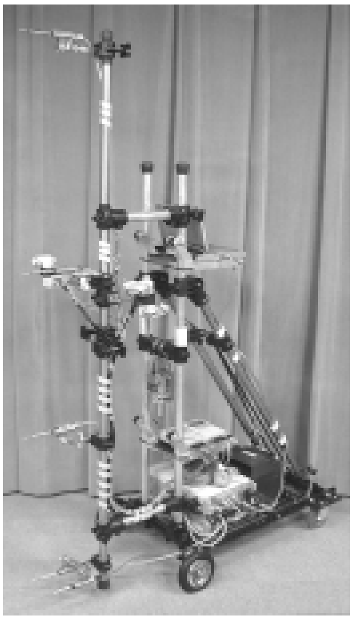
⑲ Is the present <u>thermal environment</u> acceptable?

☐Acceptable ☐Unacceptable

⑳ Do you have any other comments about this environment?

Figure 5-3. Questionnaire sheet (back)

Table 5-3. Mobile measurement cart and measurement items for thermal environment



	Measurement items	Instruments	Height (m)
Occupied zone	Air temperature	C-C thermocouples	0.1 / 0.6 / 1.1 / 1.7
	Air velocity	Omnidirectional heated anemometer	0.1 / 0.6 / 1.1 / 1.7
	Humidity	RH sensor	0.1 / 1.1
	Total radiation	Directional radio-meter (0.3-4.0μm)	1.1 (6 directions)
	Solar radiation	Silicon pyranometer (0.4-1.1μm)	1.1 (6 directions)
	Surface temperature	C-C thermocouples	Seat and ground
Outdoor condition	Air temperature	Thermister	
	Humidity	RH sensor	
	Solar radiation	Solar meter	

Figure 5-4. Questionnaire survey and measurement of thermal environment

Table 5-4. Collected number of questionnaire responses

Building	Summer	Autumn	Winter	Spring	Total
O	137	143	49	119	448
T	183	191	132	144	650
P	151	167	122	140	580
B	160	155	130	125	570
Total	631	656	433	528	2248

5.2.4 Calculation of Mean Radiant Temperature (MRT)

Long wave radiation: Directional long wave radiation L_k [W/m^2] was calculated by subtracting the measurement value of the pyranometer $I_{net,k}$ [W/m^2] from the measured total radiation $R_{net,k}$ [W/m^2] for each direction. The subscript k represents the six directions for up, down, right, left, front, and back.

$$L_k = R_{net,k} - I_{net,k} \tag{5-1}$$

Solar radiation: In HVAC buildings P and B where direct solar radiation rarely reached the occupant, the measured solar radiation was considered to be diffuse radiation. For non-HVAC buildings O and T, direct solar radiation normal to the sunray $I_{dir,n}$ [W/m^2] was calculated from the global radiation (Udagawa and Kimura, 1978). Time, date, location, and readings of the upward direction of the pyranometer $I_{net,up}$ were used as the input variable. From the orientation of each sensor, direct solar radiation entering each direction $I_{dir,k}$ was calculated by trigonometric function. These values were subtracted from each directional pyranometer reading $I_{net,k}$ to derive diffuse solar radiation $I_{dif,k}$ [W/m^2].

$$I_{dif,k} = I_{net,k} - I_{dir,k} \tag{5-2}$$

Net radiation on man: Long wave radiation and diffuse solar radiation was assumed to be absorbed by the effective radiation area. Since all respondents were seated, a value of 0.696 was used as effective radiation area factor A_{eff} [-] (Fanger, 1970). Short wave absorptance a [-] of clothed body was assumed to be 0.66. Directional diffuse total radiation $R_{dif,k}$ [W/m^2] was weighted according to the projected area of the human body (Olesen et al., 1989) and averaged for diffuse total radiation R_{dif} [W/m^2].

$$R_{dif,k} = L_k + aI_{dif,k} \tag{5-3}$$

$$R_{dif} = 0.127(R_{dif,up} + R_{dif,down}) + 0.186(R_{dif,right} + R_{dif,left} + R_{dif,front} + R_{dif,back}) \tag{5-4}$$

The direct total radiation on man R_{dir} [W/m^2] was assumed to be $I_{dir,n}$ absorbed by the body surface area directly lit by the sun. A constant value of 0.2 was used for γ_p [-], irradiated area expressed as fraction of Dubois area, since only small differences existed for irradiated area of a seated man for different solar altitudes (Breckenridge and Goldman, 1972).

$$R_{dir} = a\gamma_p I_{dir,n} \quad (5\text{-}5)$$

Net radiation on man R [W/m^2] was calculated by the sum of equations (5-4) and (5-5).

$$R = R_{dir} + A_{eff} R_{dif} \quad (5\text{-}6)$$

Surface temperature of an imaginary uniform enclosure *MRT* [°C] was derived from the following equation. σ is the Stefan Boltzmann constant (5.67 x 10^{-8} [W/m^{2}K^4]).

$$A_{eff}\sigma(MRT + 273.15)^4 = R_{dir} + A_{eff} R_{dif} \quad (5\text{-}7)$$

$$MRT = \left(\frac{a\gamma_p I_{dir,n} / A_{eff} + R_{dif}}{\sigma} \right)^{0.25} - 273.15 \quad (5\text{-}8)$$

5.3 RESULTS AND DISCUSSION

5.3.1 Outdoor Climatic Conditions

Figure 5-5 shows the daily mean outdoor temperature and humidity of all survey days calculated from the meteorological data of Tokyo. Tokyo area belongs to the temperate climate zone having four distinctive seasons. The climate is hot and humid in summer, cold and dry in winter, and intermediate during spring and autumn. The general seasonal description applies to the seasonal classification of the present survey.

Daily fluctuation of outdoor temperature was calculated for each season from the meteorological data of survey days. The results are given in Figure 5-6. Daily minimum temperature was generally observed at around 6:00 and maximum at 14:00. Difference in daily maximum and minimum temperature was approximately 5.5 °C in autumn and winter and 4 °C in summer and spring, showing that temperature variation was larger during autumn and winter seasons.

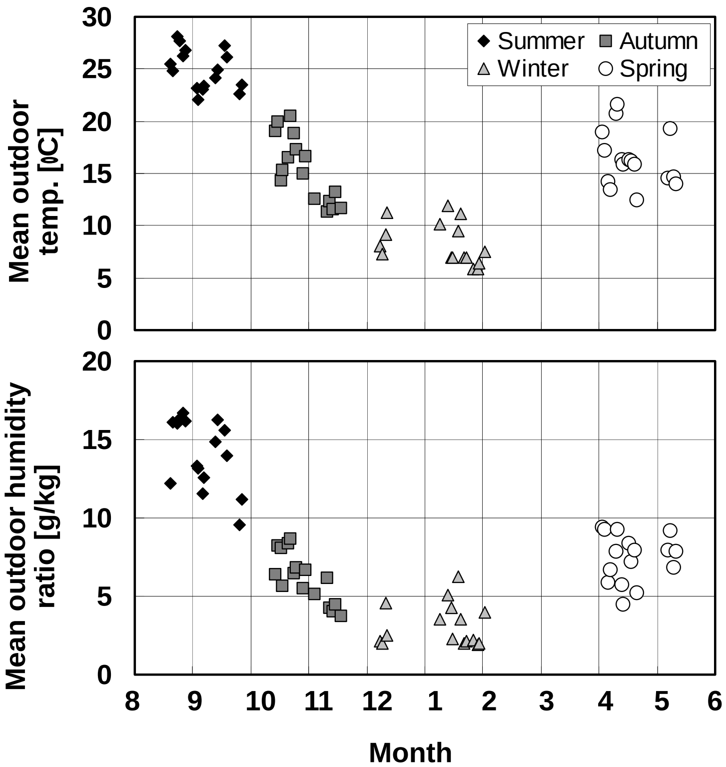


Figure 5-5. Daily mean outdoor temperature and humidity of all survey days

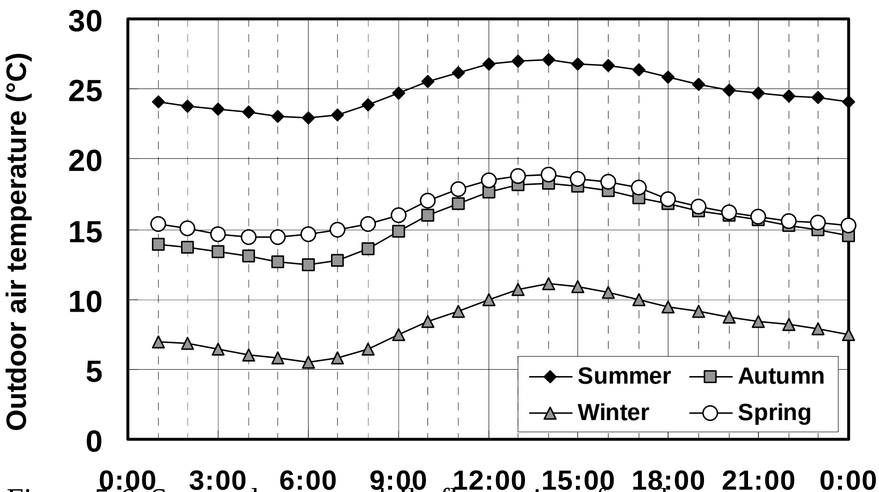


Figure 5-6. Seasonal average daily fluctuation of outdoor temperature

5.3.2 Thermal Environmental Characteristics

Thermal environmental characteristics of the occupied zone were analyzed according to the environmental classification of the 4 semi-outdoor environments. Air conditioned atria will be referred to as “HVAC” and non-air conditioned spaces as “non-HVAC”.

Relationship between outdoor air temperatures and air temperatures of the occupied zone measured around the questionnaire respondent with mobile measurement cart are given in Figure 5-7. Air temperature closely coincided the outdoor temperature in non-HVAC buildings. Links between the two temperatures were also observed in HVAC buildings, but occupied zone was generally kept between 15-29 °C.

Mean radiant temperatures of the occupied zone are plotted against air temperature of the occupied zone in Figure 5-8. MRT close to air temperature was observed in HVAC buildings while prominently higher values were recorded in non-HVAC buildings due to solar radiation.

Humidity ratio of occupied zone and outdoor are presented in Figure 5-9. Mild humidity control was confirmed in both HVAC buildings, especially when outdoor humidity was high. Live plants grown in the atrium of building P contributed to keep the humidity higher in lower ranges as opposed to building B.

Relative frequency of air velocity observed within the occupied zone is shown in Figure 5-10. Majority of mean air velocity measured in HVAC buildings were below 0.3 m/s, while the peak frequency of 0.6 m/s and maximum value of 2.6 m/s was observed in non-HVAC buildings.

All four thermal parameters showed similar characteristics within each environmental category, and this classification of “non-HVAC” and “HVAC” will be employed for the further analyses.

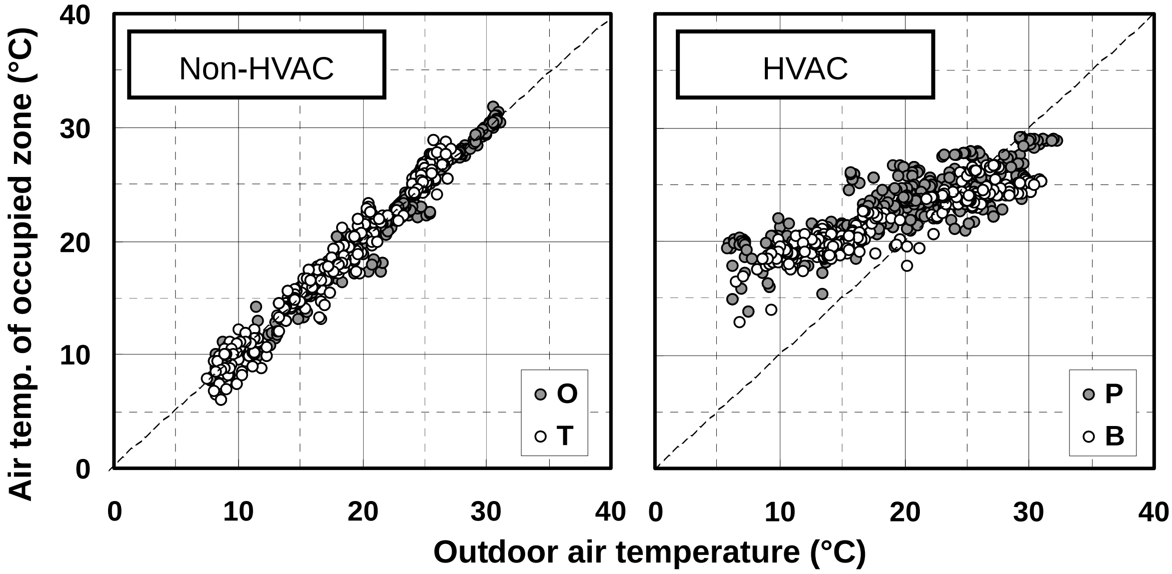


Figure 5-7. Outdoor air temperature and air temperature of occupied zone

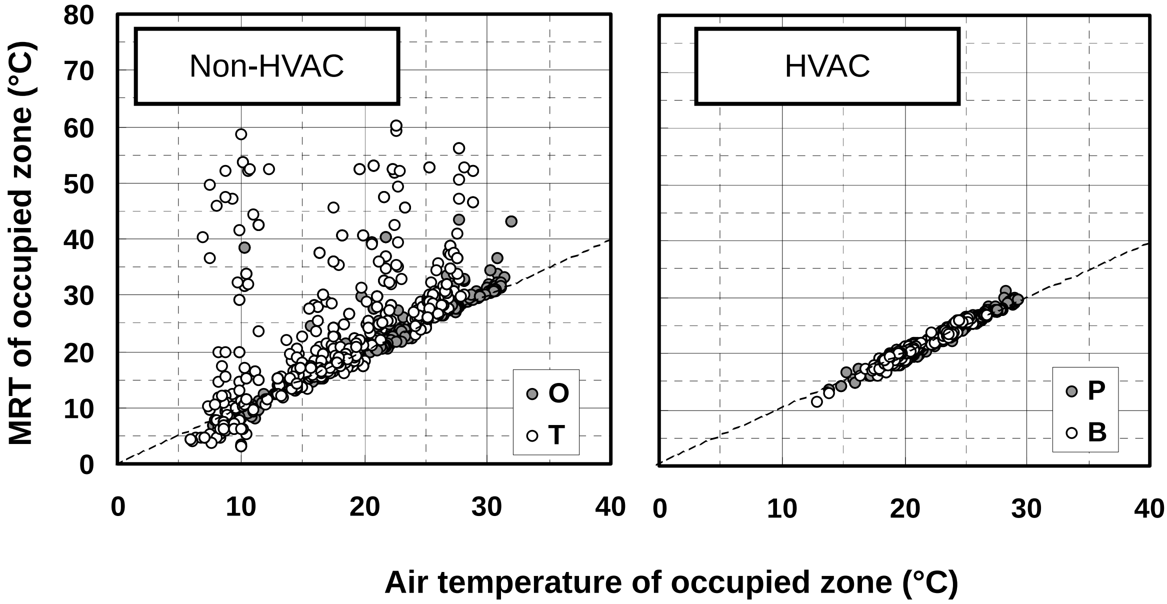


Figure 5-8. Air temperature and mean radiant temperature of occupied zone

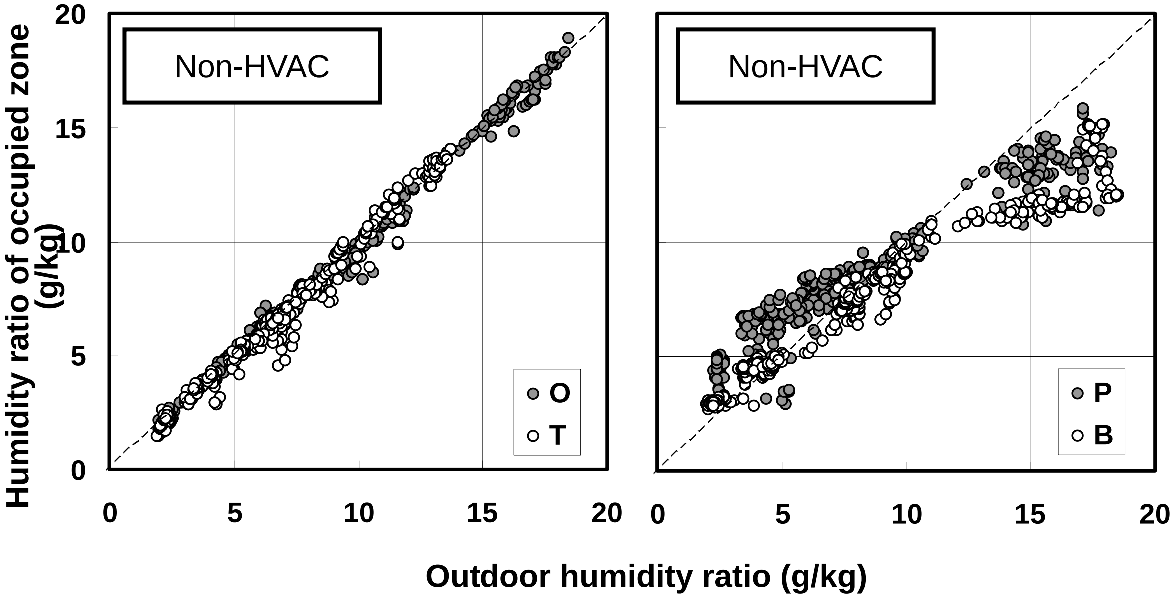


Figure 5-9. Outdoor humidity and humidity of occupied zone

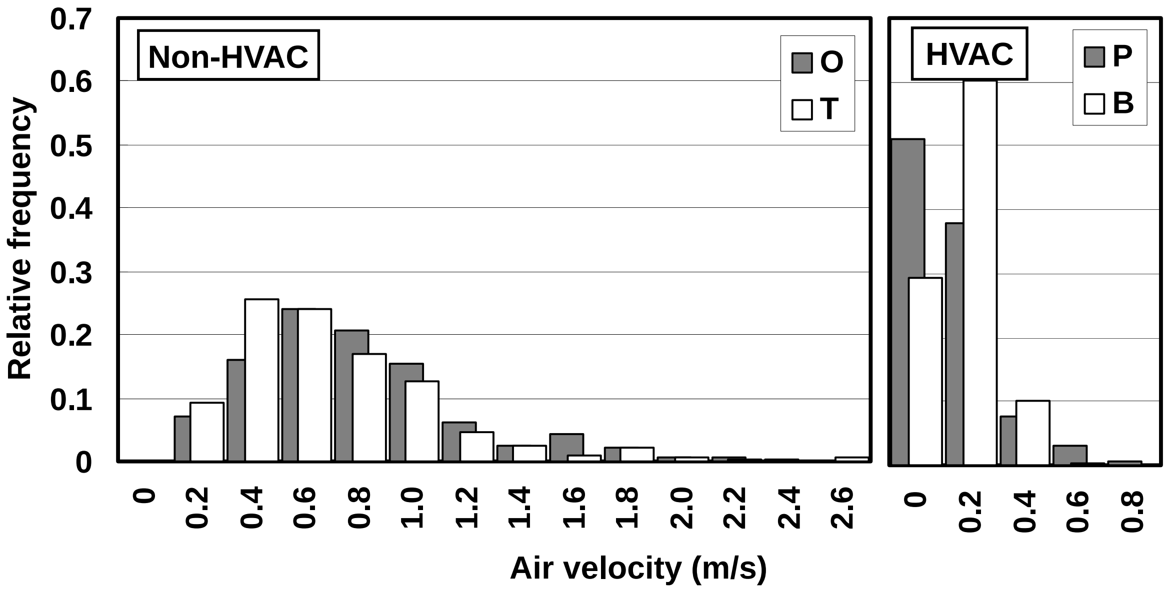


Figure 5-10. Relative frequency of air velocity in occupied zone

5.3.3 Occupancy Conditions

Questionnaire results concerning the background information of the respondents are given in Figure 5-11. Occupation of respondents was asked to illustrate the degree of freedom in clothing, as business man/woman would be restricted of their clothing selection on working days.

In buildings O, P and B annexed to an office building, 70 % or more of the occupants were in their 30's or younger, and more than 60 % were business man/woman. Population in building T annexed to a department store was slightly different, with larger percentage of students, 40 %. The ratio of males to females was approximately 50 to 50 in all buildings except building P, where 70 % were females.

Over 60 % of occupants answered the purpose of their stay to be "resting" or "meal (lunch)" in all buildings. Other purposes included in the questionnaire such as "reading", "chatting", "smoking" and "mobile phone" along with the two given above could be regarded as voluntary activities. The contrary would be "waiting", where an occupant is required to wait in the environment regardless of his/her comfort condition. The percentage of "waiting" plus "others" was 17 % of entire respondents, and majority of occupant activities, 83%, is considered to be voluntary.

Occupancy in present semi-outdoor environments can be regarded as arbitrary, as opposed to imposed occupancy in climate chambers or other scenes of indoor environment such as offices or schools. This implies that occupants in semi-outdoor environments have greater freedom in selection of their own occupancy condition than indoor environments.

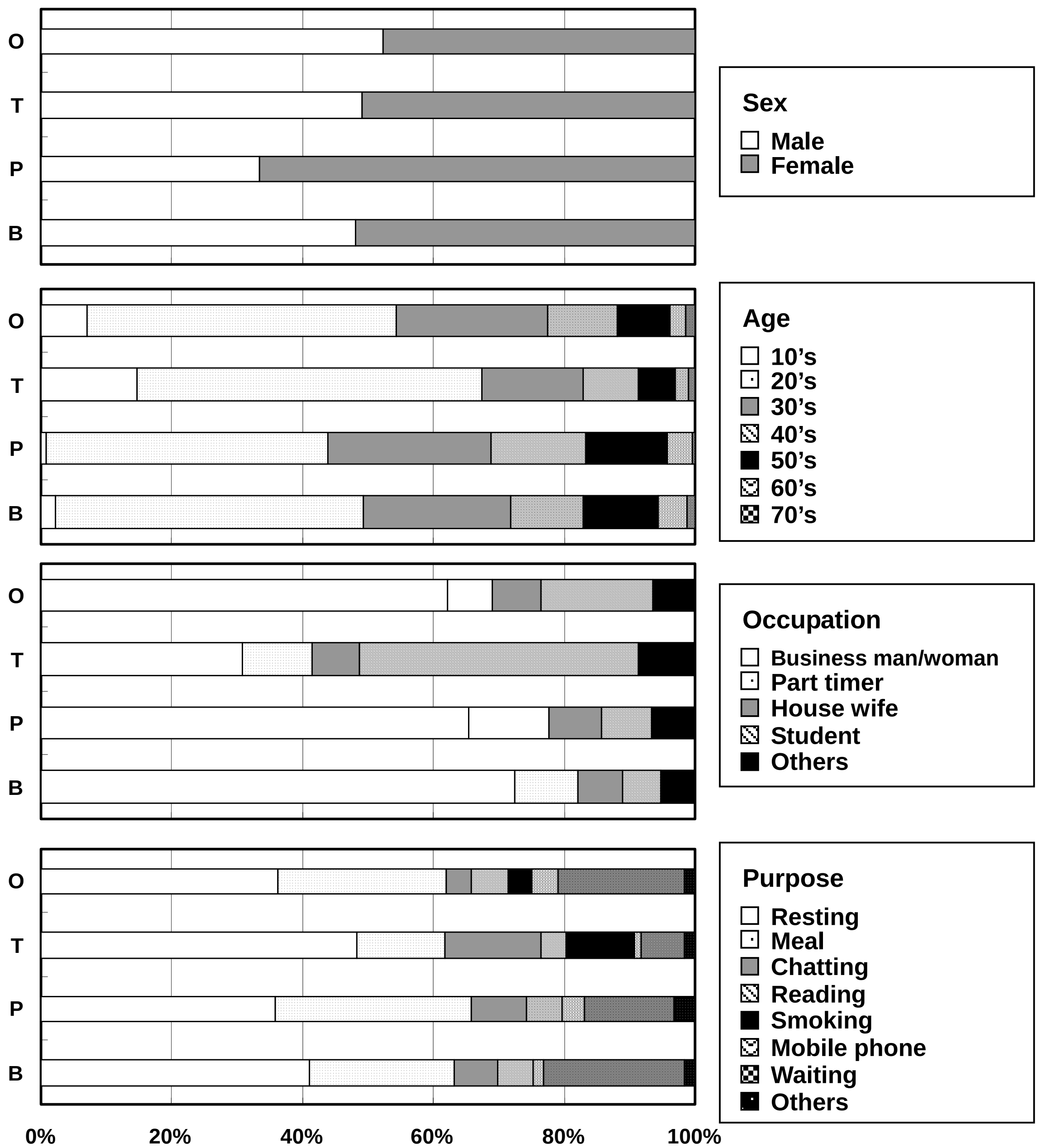


Figure 5-11. Questionnaire results on background information of respondents

Average occupancy periods for each building are given in Table 5-5. Although slight decrease was observed in winter, occupancy periods in non-HVAC buildings were approximately 10 minutes all year round for both O and T. The values were not consistent in HVAC buildings, 20 minutes and 15 minutes for buildings P and B respectively. Average occupancy period was longer in building P where a section of the area was equipped with lounge chairs compared to metal meshed benches in building B. Quality of the furniture may have an impact on occupancy period in close structured HVAC buildings, while the effect could be considered to be smaller in open structured semi-outdoor environment where installation of high quality comfort chairs would be unrealistic.

Diurnal variation in the number of occupants, seasonal average of four days, is presented in Figure 5-12 to 5-15 for buildings O, T, P and B respectively. Evident peak was observed around 12:30 in office buildings O, P and B when office workers occupied the area for lunchtime. Number of females was greater during that period. Unique profile was confirmed in department store T where the number grew from morning towards the afternoon, and remained constant or even higher until the end of survey. Majority of occupants were males in Building T. Apparent decrease was observed during winter in both non-HVAC buildings, while the profile remained fairly constant throughout the year in HVAC buildings.

Table 5-5. Average occupancy period

		Summer	Autumn	Winter	Spring	All
Non-HVAC	O	0:11 (551)	0:10 (503)	0:06 (327)	0:09 (617)	0:09 (1998)
	T	0:13 (592)	0:11 (534)	0:08 (383)	0:12 (217)	0:11 (1726)
HVAC	P	0:17 (539)	0:27 (447)	0:26 (383)	0:18 (551)	0:21 (1920)
	B	0:17 (431)	0:14 (358)	0:13 (440)	0:15 (324)	0:15 (1552)

*(population)

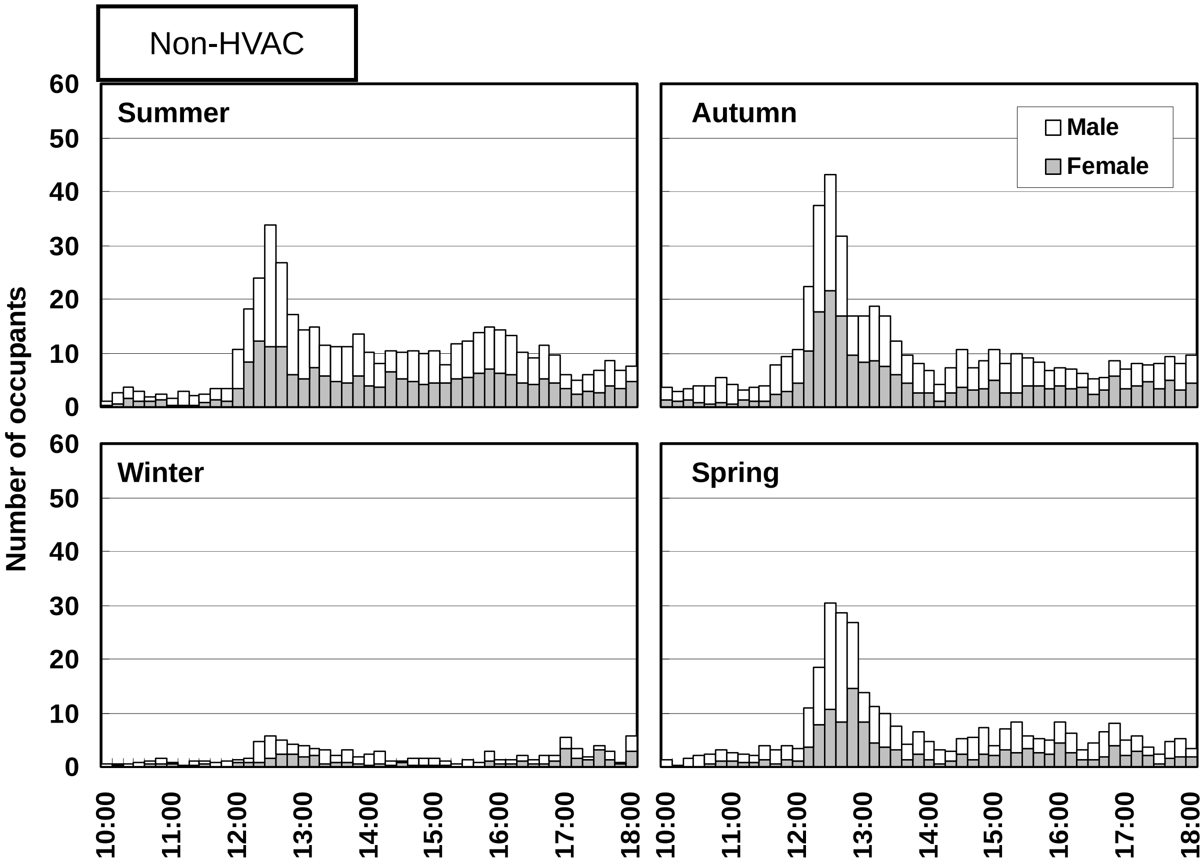


Figure 5-12. Variation in number of occupants in non-HVAC building O (seasonal average of 4 days)

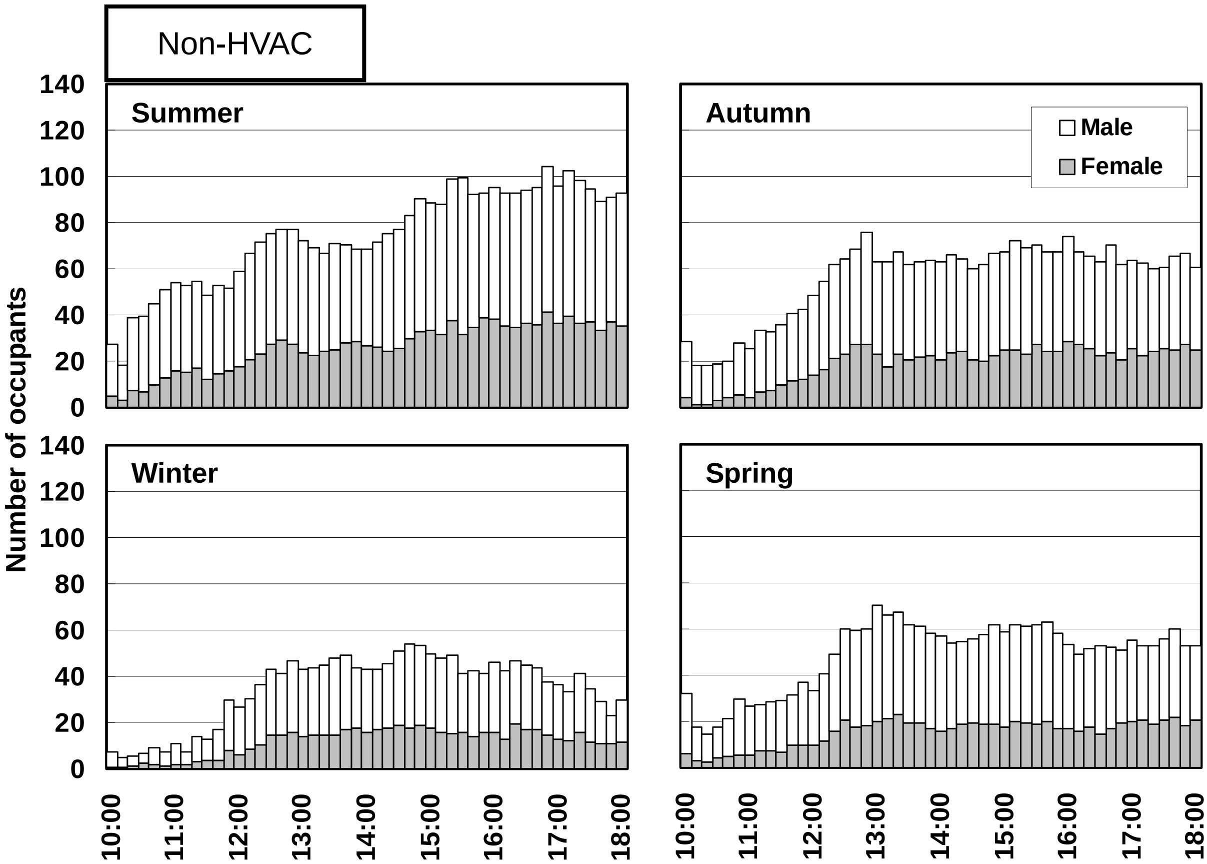


Figure 5-13. Variation in number of occupants in non-HVAC building T (seasonal average of 4 days)

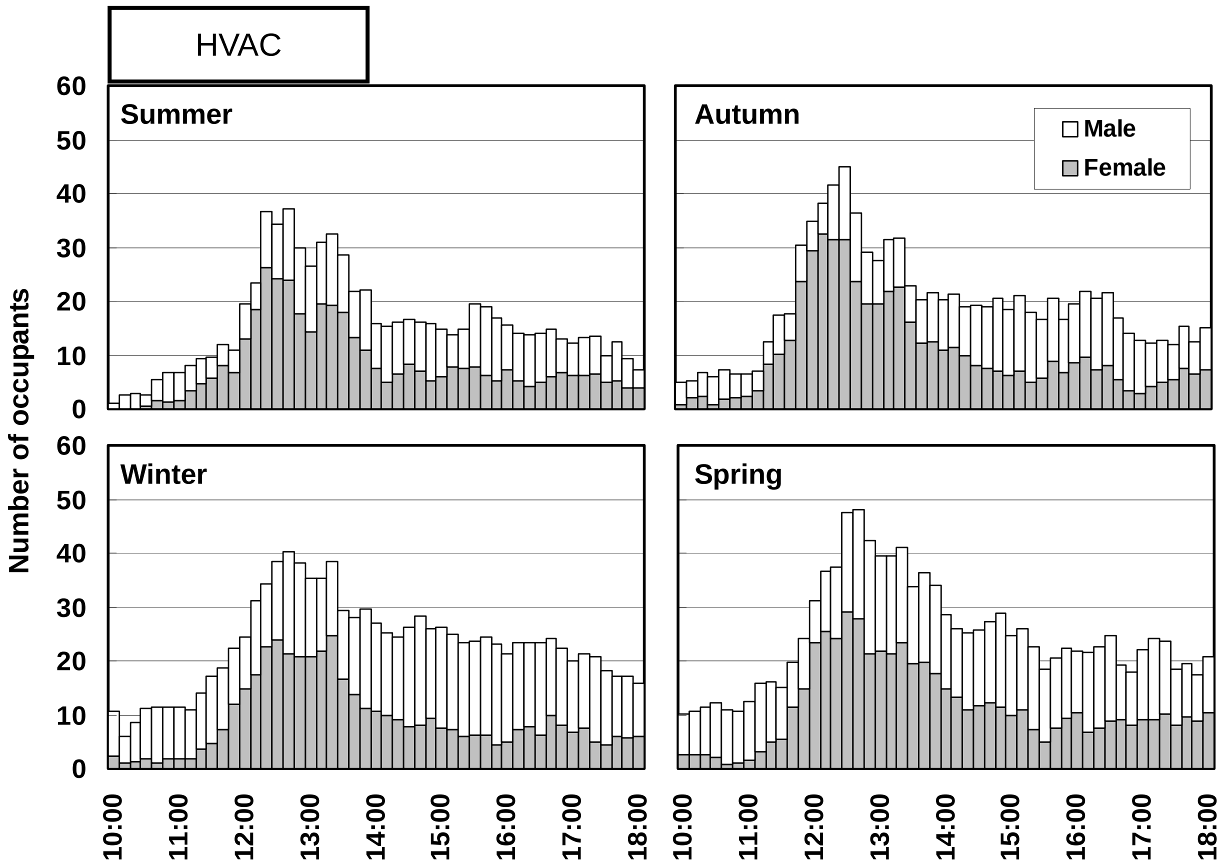


Figure 5-14. Variation in number of occupants in HVAC building P (seasonal average of 4 days)

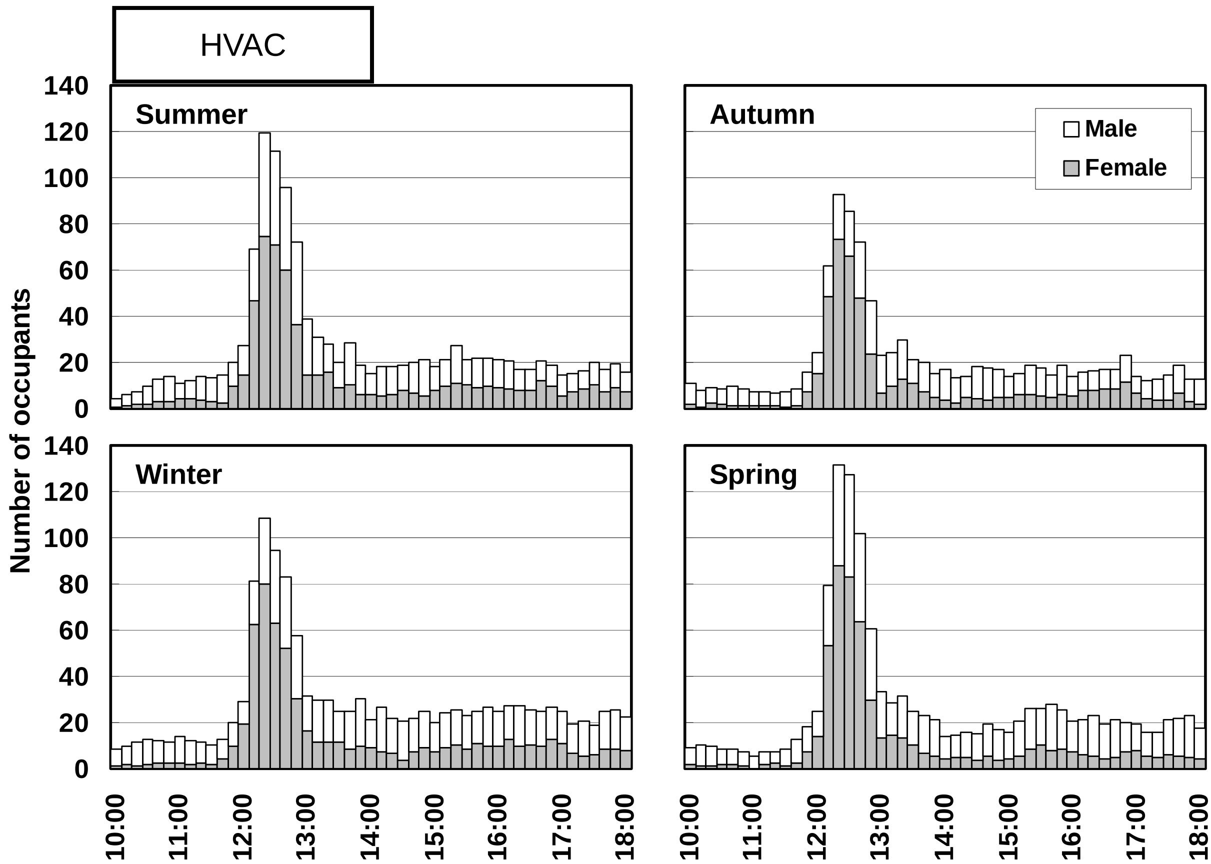


Figure 5-15. Variation in number of occupants in HVAC building B (seasonal average of 4 days)

Selection of occupancy conditions could be regarded as a form of behavioral adaptation. It is likely that occupants would choose the environment that they feel comfortable unless circumstances limit their freedom to do so. The degree of freedom to choose their own environment is considered to be higher in semi-outdoor environments than indoors. If the environment did not match their expectation, and other forms of adaptation were not sufficient to maintain their comfort, occupants may choose not to stay. The occupancy conditions were investigated in relation to the thermal environment of the occupied zone.

The daily total number of occupants counted for each survey day is plotted against the mean air temperature of the occupied zone on that day in Figure 5-16. The data of the days when an exhibition took place in the survey area was excluded as exceptions. The number of occupants was confirmed to have a strong linear relationship with the air temperature of occupied zone in non-HVAC buildings while no correlation was found in HVAC buildings.

Occupancy period was also linearly correlated with air temperature of the occupied zone in non-HVAC buildings as presented in Figure 5-17. The gradient was similar for both buildings O and T, which approximately equalled to one minute decrease in average occupancy period for each 3 °C decrease in daily mean air temperature. No correlation was found for HVAC buildings.

Instantaneous effect of environmental change such as solar radiation and wind on occupancy condition could not be analysed from the present results, due to a large hourly fluctuation in the number of occupants and period of occupancy in all buildings.

From the results above, it would be fair to recognize that occupants in non-HVAC semi-outdoor environments were more responsive to the thermal environment, and prefer warmer weather to cooler one for short-term occupancy. Nikolopoulou et al. (2001) reported similar results on a link between the number of occupants and globe temperature from the UK field survey in urban outdoor spaces, analogous to non-HVAC semi-outdoor environment in this study. However, this was not the case for HVAC buildings, while non-HVAC buildings showed a linear fit for number of occupants even within the same narrow temperature range of HVAC buildings, 18-28 °C. The purpose of use was similar between the two types of buildings as confirmed in the previous section, and the prominent difference lies in the level of environmental control. The cause of variation in the occupancy conditions in HVAC buildings could not be specified from the present survey, but factors other than thermal environment such as type of furniture seems to have a greater impact.

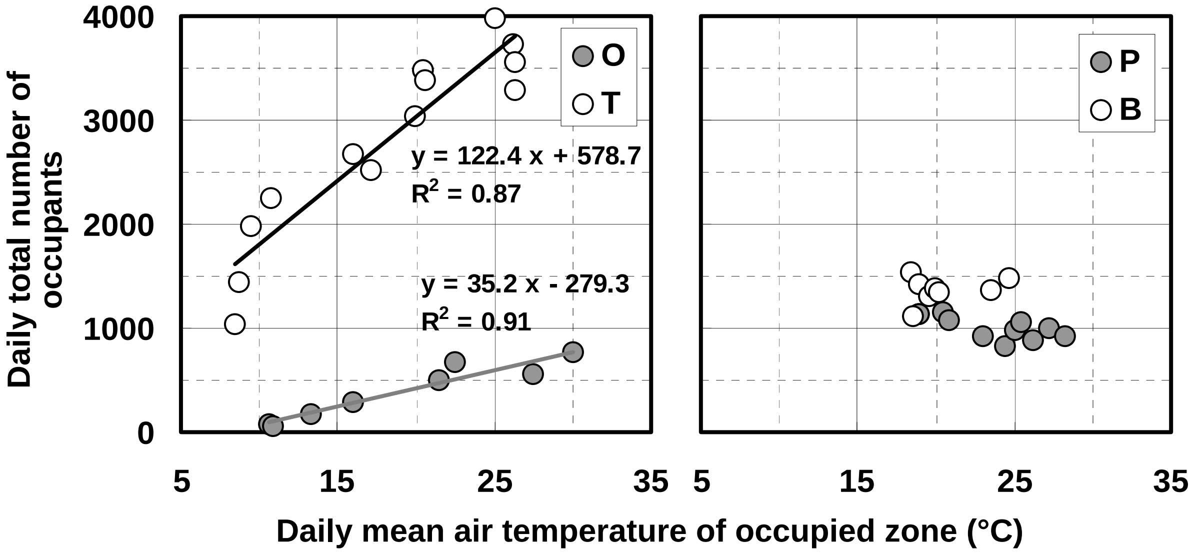


Figure 5-16. Daily mean outdoor air temperature and daily total number of occupants

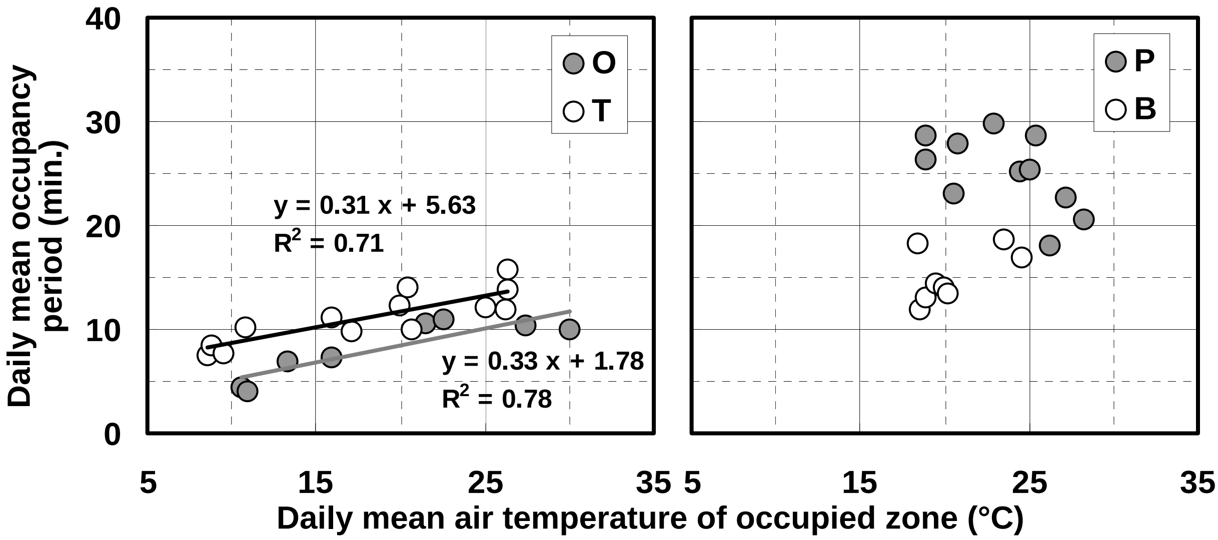


Figure 5-17. Daily mean outdoor air temperature and daily mean occupancy period

5.3.4 Clothing Adjustment

Clothing adjustment is probably the most documented form of behavioral adaptation. Humphreys (1977) indicated that clothing of visitors at zoo closely related to any other environmental variables, and that people were less successful in adjusting their clothing to radiation, humidity, or air velocity. Field studies on clothing are typically conducted by surveyor's visual observation or using a garment checklist of specific clothing items. A combination of both methods was employed in this survey for precise examination of clothing adjustment. The questionnaire sheet presented in Figure 5-2 asked specifically on the clothing items worn "at the moment" to observe the correspondence with immediate thermal environment measured by the mobile measurement cart. However, mistakes could happen especially in short-term occupancy spaces where a respondent may have worn a coat prior to occupancy and have it in hand at the time of questionnaire. In order to avoid apparent mistakes, visual observation of a surveyor was also recorded simultaneously using the same checklist.

Each clothing item in the questionnaire was assigned an insulation value according to ISO 9920 (1995) and summed for total insulation. Representative values and results of the t-test conducted between males and females are given in Table 5-6. Female clothing was significantly smaller than males in HVAC building throughout the year, while the difference was insignificant in autumn and winter in non-HVAC buildings. Results of the field studies in offices indicated that females generally have smaller clothing insulation than males (Schiller et al., 1988), but it was not found to apply for non-HVAC semi-outdoor environments in cool seasons.

Seasonal distributions of clothing in 0.1 clo intervals are presented in Figure 5-18. Normal distribution was observed in non-HVAC buildings for all seasons. The values were widely spread in HVAC buildings, illustrating the variety in clothing patterns. Spikes in certain clothing insulation were observed in HVAC buildings due to typical business attire for office work. Clothing with the highest frequency was the same for all seasons between non-HVAC and HVAC buildings, 0.4, 0.9, 1.1 and 0.9 clo respectively for summer, autumn, winter and spring.

Table 5-6. Average clothing insulation (clo)

	Non-HVAC			HVAC		
	Male	Female	All	Male	Female	All
Summer	**0.54	0.46	0.49	**0.67	0.49	0.56
Autumn	0.90	0.94	0.92	**0.94	0.86	0.89
Winter	1.28	1.26	1.27	**1.34	1.08	1.21
Spring	*0.90	0.85	0.88	**0.86	0.73	0.78

*: p<0.05, **: p<0.01

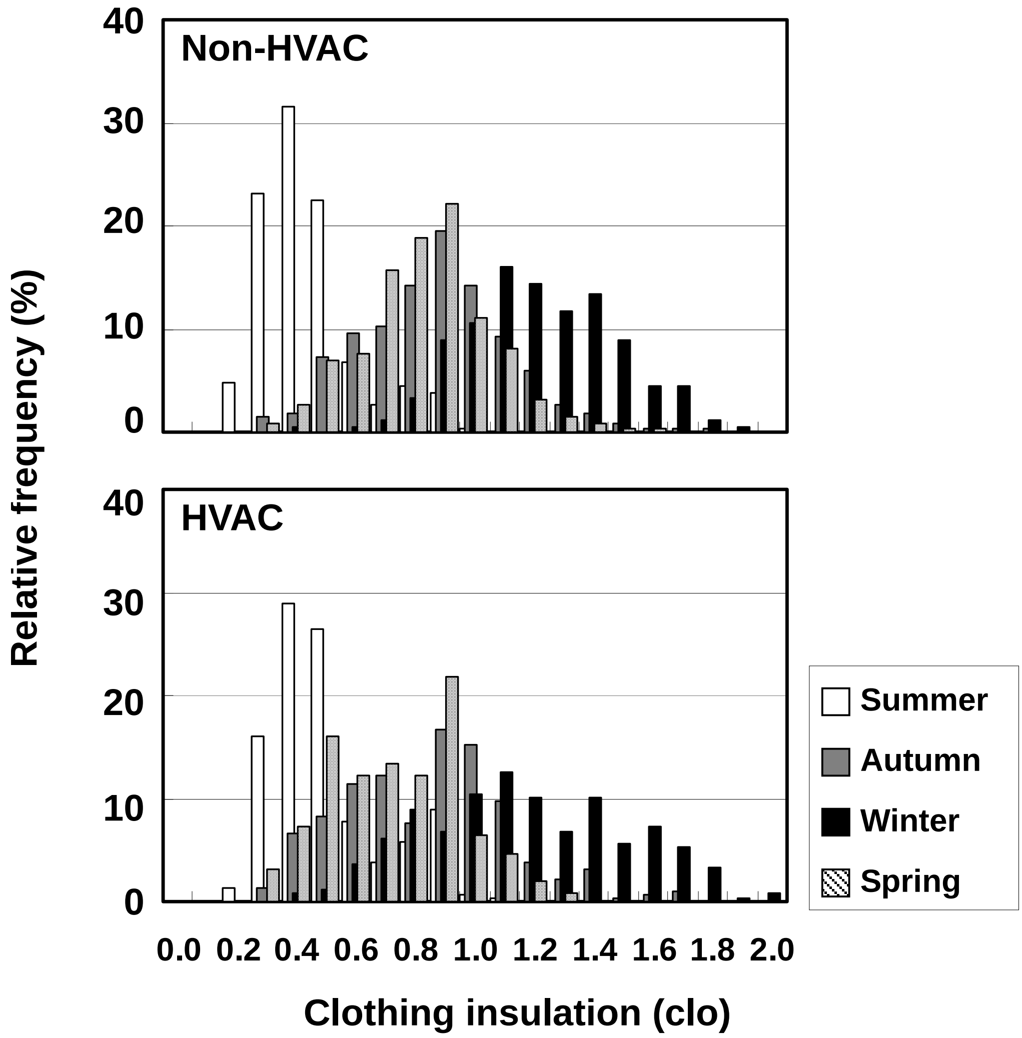


Figure 5-18. Daily mean outdoor air temperature and daily mean occupancy period

Air temperatures of the occupied zone measured simultaneously with questionnaire were rounded into 0.5 °C increments and corresponding mean clothing insulation values were calculated to examine the clothing adjustment for a given thermal environment. The results are presented in Figure 5-19. The size of the plot represents the number of population used to calculate each mean value. Weighted linear regression was applied for each season separately.

Clothing was linearly correlated with the air temperature of the occupied zone in both non-HVAC and HVAC buildings. Seasonal differences in the gradient of linear regression were found for both non-HVAC buildings and HVAC buildings. The gradient of linear regression denotes the degree of clothing change against air temperature change of the occupied zone. Summer and spring showed a similar gradient as well as autumn and winter. Gradients were found to be larger in HVAC buildings.

Note that the profile of HVAC buildings would appear quite similar to non-HVAC if the temperature range were stretched to that of non-HVAC. Relationship was sought among mean clothing insulation and mean outdoor temperature for each day. The results are presented in Figure 5-20. Clothing adjustment in relation to outdoor temperature was almost identical for HVAC buildings and non-HVAC buildings, with the slight difference of 0.05 in the intercept of regression fit. Decrease of 2.5 °C in daily mean outdoor temperature equaled a 0.1 clo increase in clothing insulation. Morgan et al. (2002) conducted a series of measurements on clothing of the visitors at the department store, and concluded that clothing worn was irrespective of indoor temperature and dependant on outdoor temperature. Air temperature of the occupied zone in HVAC buildings was linked with outdoor temperature as presented in Figure 5-7, and clothing seemingly linked with environment in occupied zone. When examined for a year-round period, occupants were adjusting their clothing mainly for outdoor condition in semi-outdoor environments, whether they were air conditioned or not.

The gradient of seasonal clothing change against air temperature could be divided into two groups; summer-spring and autumn-winter. The gradient was larger for autumn-winter group, suggesting a more delicate clothing adjustment in these seasons. Figure 5-6 of average daily air temperature variation depicts the fact that temperature changes are larger in autumn and winter during the day. The occupants were dressed for the lower end of the daily temperature range. Seasonal climatic characteristic, not only in terms of mean outdoor temperature, would need to be considered for finer prediction of clothing.

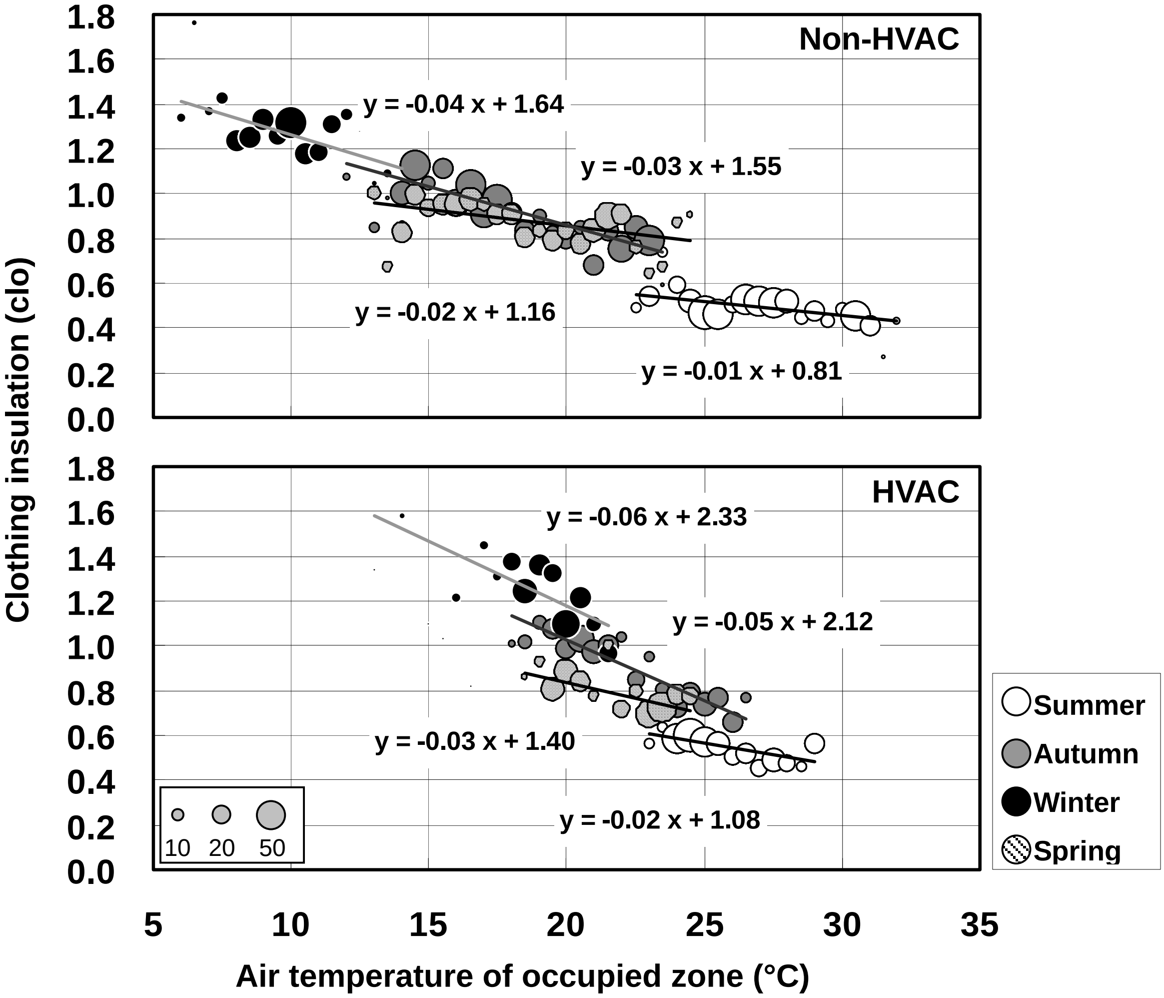


Figure 5-19. Daily mean outdoor air temperature and daily mean occupancy period

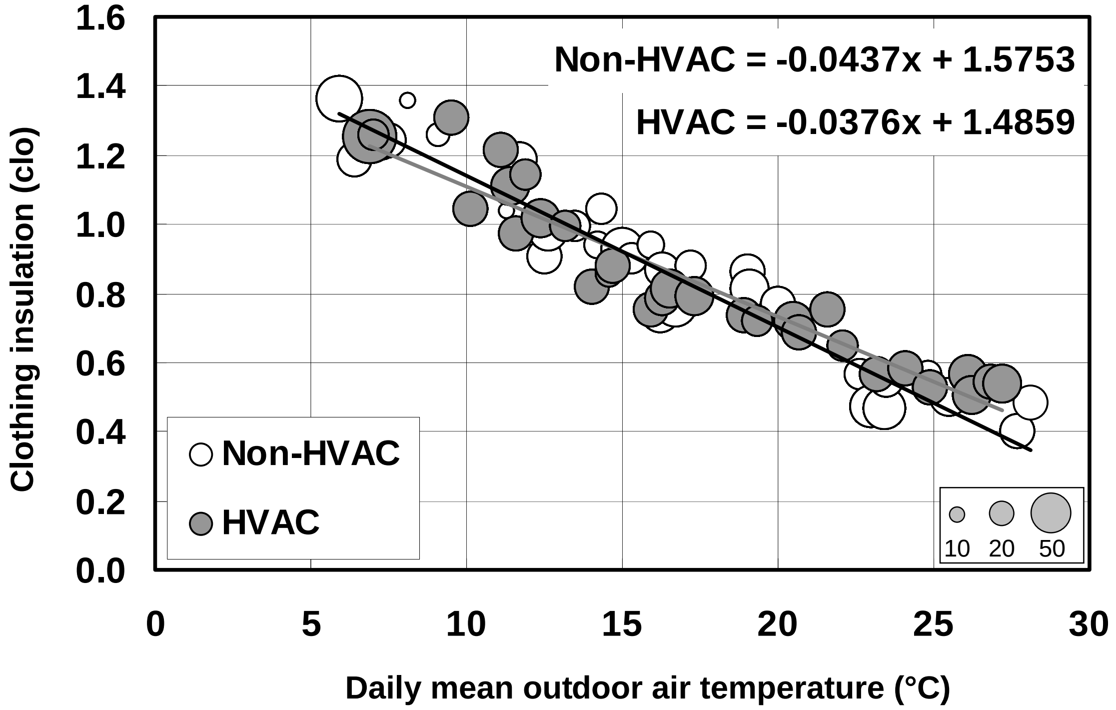


Figure 5-20. Daily mean outdoor air temperature and daily mean occupancy period

5.3.5 Neutral Temperature

Thermal indices, namely Predicted Mean Vote (PMV), Standard New Effective Temperature (SET*), New Effective Temperature (ET*) and operative temperature, were calculated for each respondent from the environmental variables measured by mobile measurement cart. Metabolic rate and clothing insulation were estimated from the questionnaire. Each clothing item was assigned an insulation value (ISO 9920, 1995) and summed for total insulation. Occupants sitting in the cushioned lounge chair of building P were added 0.15 clo for insulation of the chair (ASHRAE, 2001). No increase was considered for occupants in other buildings sitting on wooden or metal meshed benches, assuming that slight increase was compensated by the decrease of boundary air layer (McCullough et al., 1994). Little work has been done on estimation of transient metabolic rate, which may be affected by such factors as food consumption, precedent activity, and duration of the present activity. Instead of applying numerous assumptions, a constant metabolic rate of 1.1 met, a value slightly higher than sedentary seated condition, was assumed for all occupants.

Of all the thermal indices calculated for analysis, SET* achieved the highest correlation with observed thermal sensation votes as opposed to operative temperature adopted by various field studies in office environments (de Dear and Brager, 1998). Wider range of thermal environmental variables were observed in the semi-outdoor spaces compared to indoors, and a more complex thermal index which can incorporate the effects of 4 environmental variables was effective in describing the thermal environment of the occupied zone. The calculated SET* were rounded into 1.0 °C increments, and corresponding mean thermal sensation votes were derived. Weighted linear regression analysis was applied for each season and the neutral temperature (T_n) for the mean thermal sensation vote of 0 was calculated. The results are presented in Figures 5-21 and 5-22.

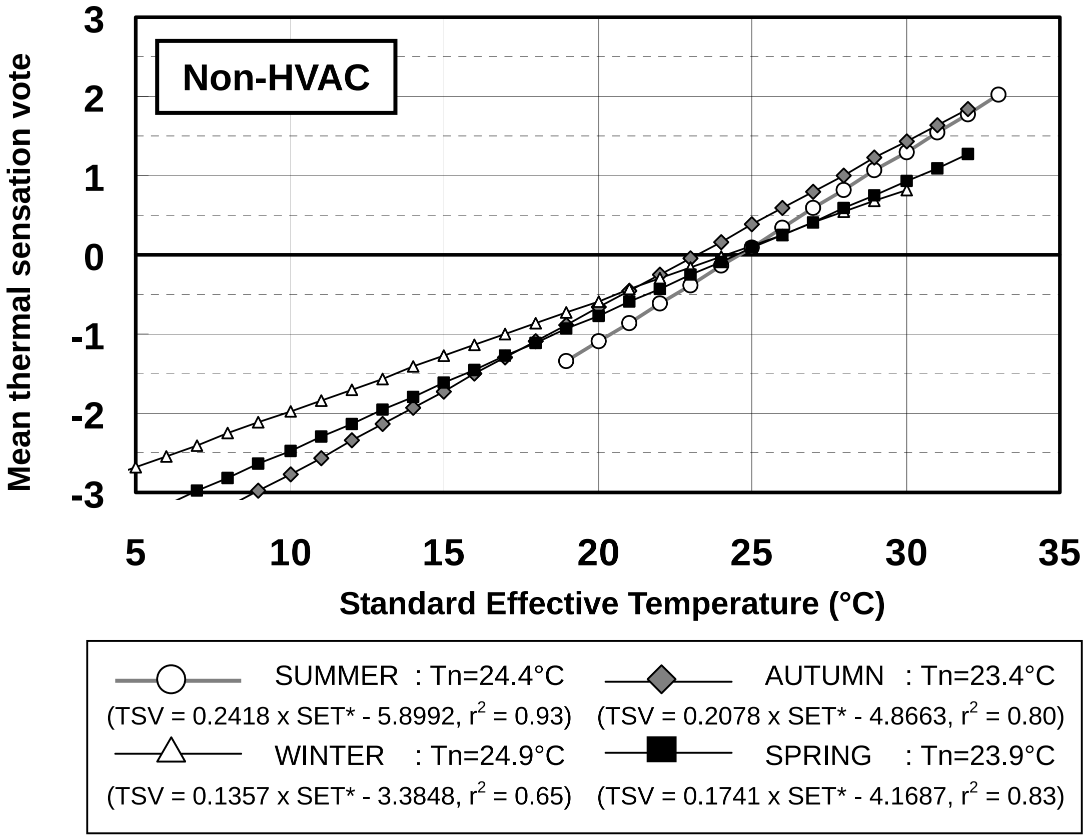


Figure 5-21. SET* and mean thermal sensation vote for non-HVAC buildings

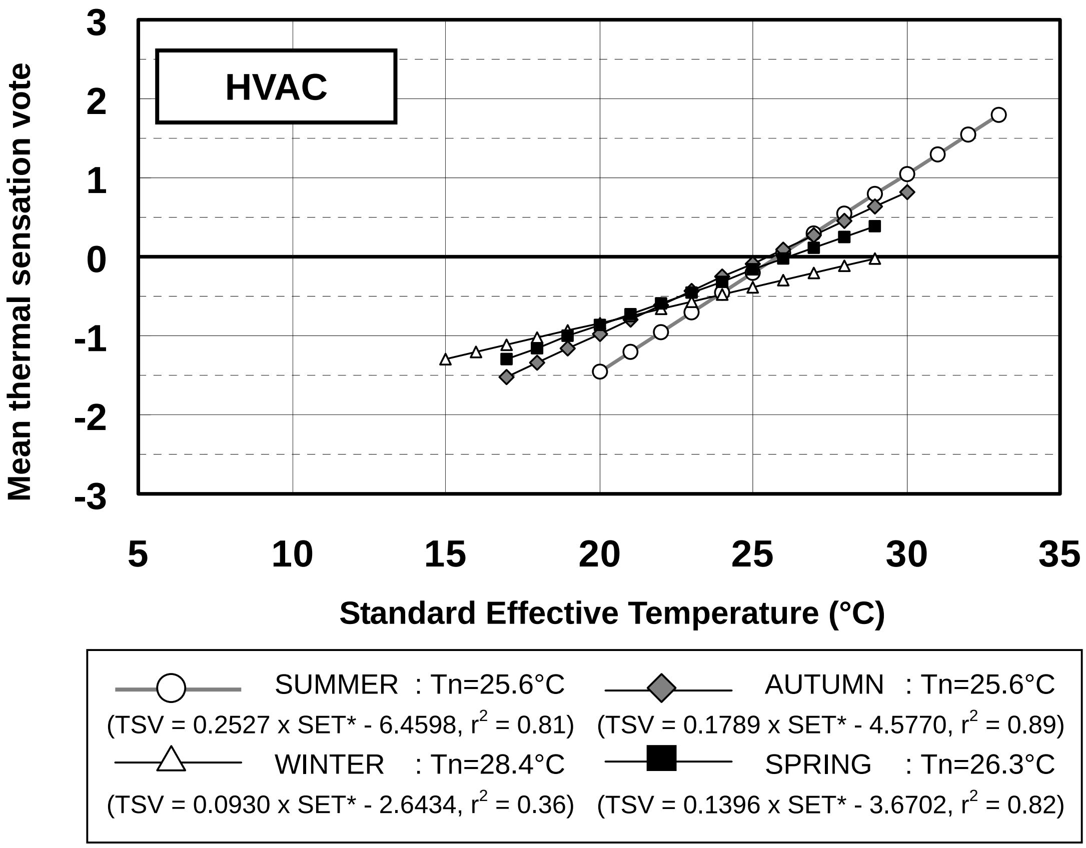


Figure 5-22. SET* and mean thermal sensation vote for HVAC buildings

The determination coefficients for linear fit equation were low in winter compared to other seasons, both in non-HVAC and HVAC buildings. The main cause is suspected to be the estimation of clothing. In order to avoid apparent errors, surveyors recorded the clothing items by visual inspection while respondents were answering the questionnaire. This procedure would be less effective in winter seasons when respondents wear buttoned up coats. Estimation of insulation for various coats and jackets themselves would also be difficult with a simple checklist. Unconscious tremor in cold environments may have contributed to slight increase in metabolic rate, whose effect has not been documented. In other seasons however, over 80% of mean thermal sensation could be explained by SET* of occupied zone. Disregarding winter, the seasonal difference of neutral temperatures was small, 1 °C range, within the type of building. The values were generally higher for HVAC buildings, approximately 26 °C, compared to 24 °C in non-HVAC buildings.

Another method for derivation of the comfort temperature is to use thermal preference scale instead of thermal sensation scales. It is argued that “neutral” on thermal sensation scale is not always the optimum, and people would prefer to be “warmer than neutral” in winter, and “cooler than neutral” in summer (McIntyre, 1980). Probit analysis (Finney, 1964) is commonly applied to the percentage of subjects wanting to feel warmer and those wanting to feel cooler, plotted against environmental temperature. This approach was tried in the present study to examine the effect of season on neutral temperature, but bias in seasonal preference votes prohibited this method. Only 4 respondents out of 419 voted the environment to be cooler during winter, and only 22 out of 614 voted to be warmer during summer.

The year-round observed relationship of mean thermal sensation vote was compared to predicted relationship. PMV was calculated for each respondent and plotted against calculated SET*. Weighted linear regression was applied in the similar manner as observed thermal sensation votes, and the result are presented in Figure 5-23. The predicted neutral temperature was identical to the observed neutral temperature in HVAC buildings. Discrepancy of 1.5 °C was found for non-HVAC. The notable difference common to both types of buildings was the gradient of curve fit equation, where predicted values were 1.5 times as large. Temperature shift of 3.5 °C would result in 1 scale unit change of predicted thermal sensation vote, while it would require approximately 6 °C for the actual change.

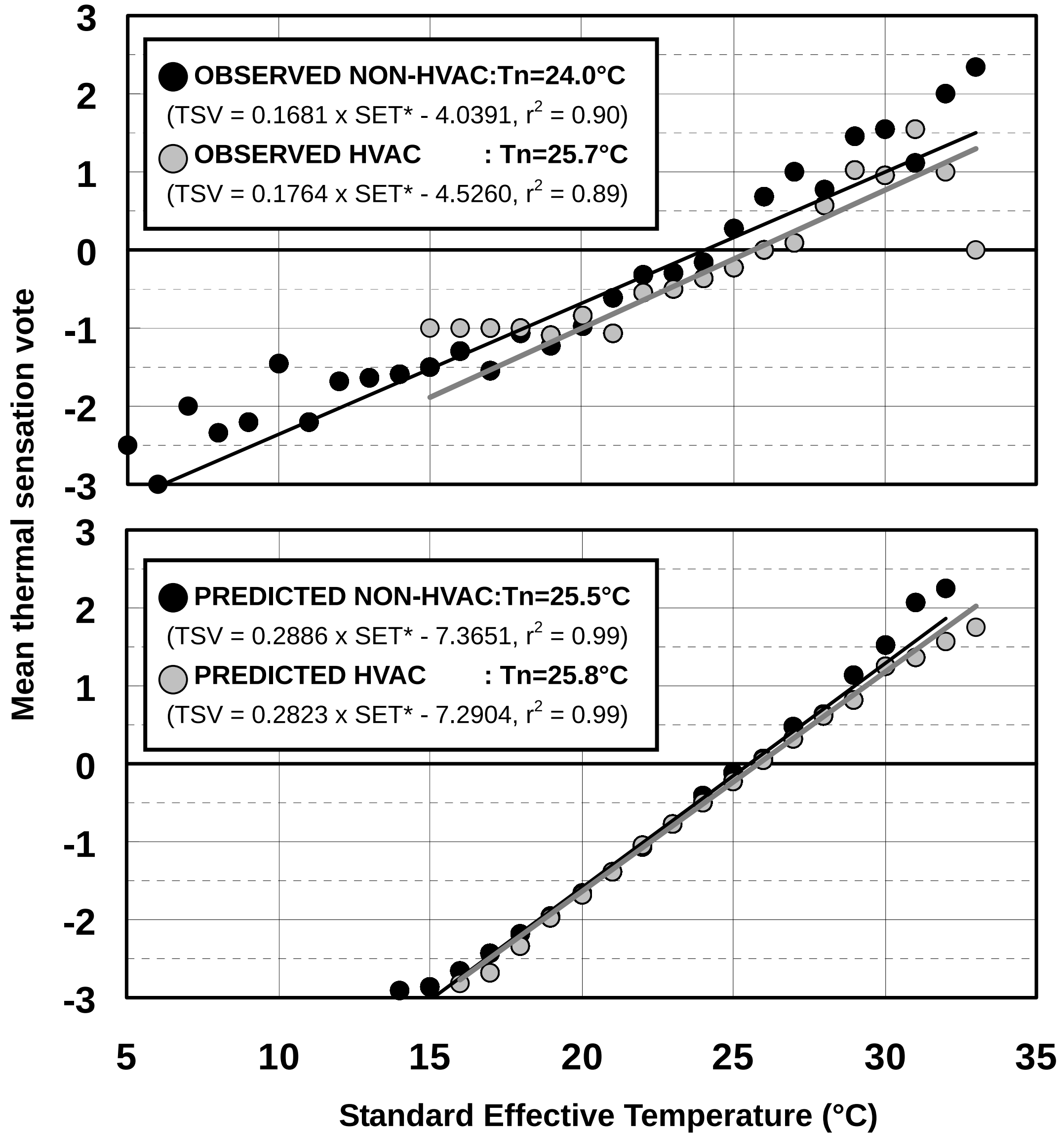


Figure 5-23. SET* and mean thermal sensation vote for HVAC buildings

5.3.6 Thermal Comfort Condition

Thermal comfort criteria in existing standards are defined in terms of percentage of dissatisfied within the given environment. Acceptability of thermal environment was asked for all the respondents in the questionnaire, but the result showed that over 80 % answered the thermal environment to be acceptable regardless of season or type of building. Therefore, alternative relationship was sought among comfort condition and thermal environment. General comfort sensation vote, not confined to thermal aspects, was included in the questionnaire. Seven-point scale of comfort was categorized into 3 classes of “comfort”, “neutral” and “discomfort”. The “comfort” and “neutral” ranges were not dependent on thermal aspects, and other factors of semi-outdoor environment such as visual aspects are thought to have influenced general comfort. However, “discomfort” was found to relate well to thermal environment, and percentage of “discomfort” votes plotted against SET* was employed to derive the comfort range. The results are presented in Figure 5-24. The PPD curve calculated for the standard condition of SET* (ta=tr, v=0.1m/s, rh=50%, 0.6 clo, 1met) was added to illustrate the difference in the comfort range.

The discomfort curves were steep in the order of PPD, HVAC and non-HVAC, implying that occupants in semi-outdoor environments were more tolerant against wider environmental temperature range. The comfort ranges in thermal comfort standards are commonly specified in terms of 90 % and 80 % acceptability ranges, and corresponding ranges were derived in Table 5-7. The 80 % acceptability range of non-HVAC buildings was approximately 18 °C, three times as large as that of PPD. The same range for HVAC buildings was twice of PPD.

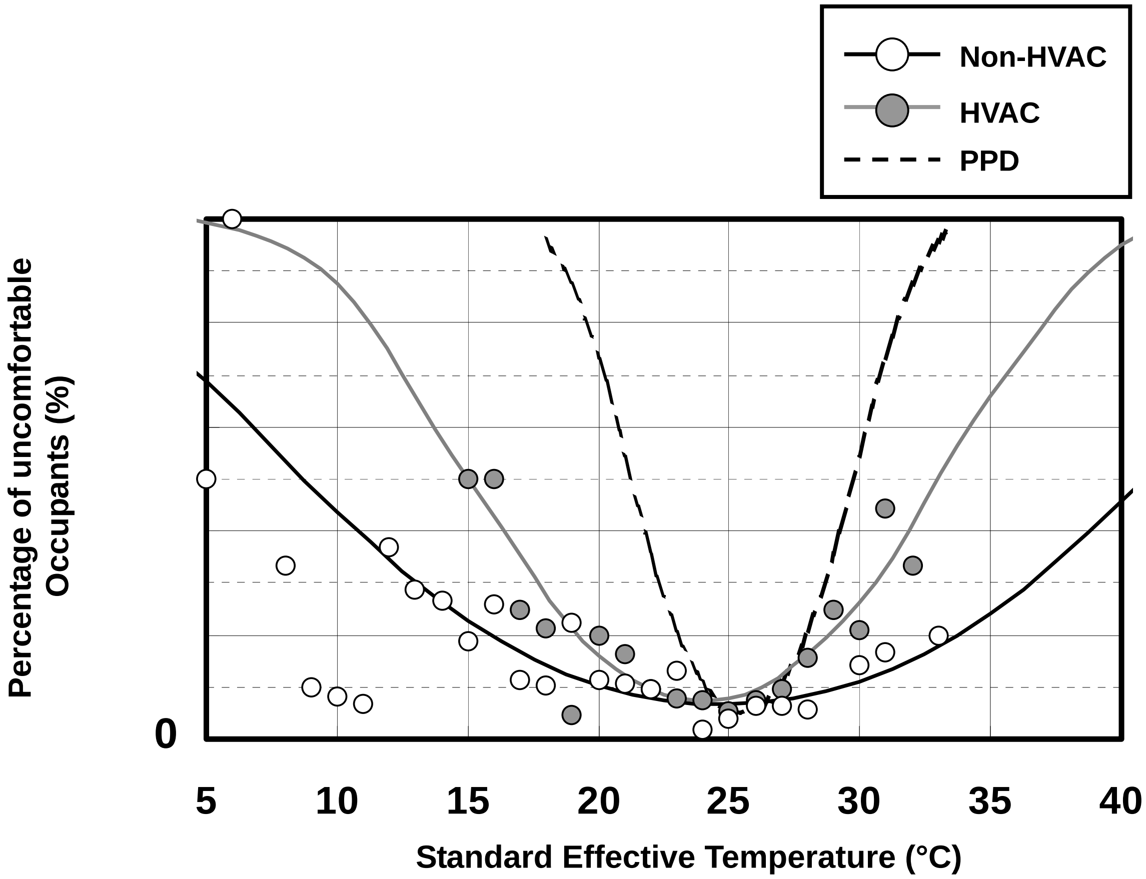


Figure 5-23. SET* and mean thermal sensation vote for HVAC buildings

Table 5-7. Temperature range which 10% and 20% of the occupants feel uncomfortable

	10 % discomfort range			20 % discomfort range		
	Low end (°C)	High end (°C)	Temperature range (°C)	Low end (°C)	High end (°C)	Temperature range (°C)
PMV	24.1	26.9	2.8	23.0	27.9	4.9
Non-HVAC	20.2	29.4	9.2	15.8	33.7	17.9
HVAC	21.8	26.3	4.5	19.2	28.9	9.7

5.3.7 Implications for Environmental Design

Adaptive model implies an environmental design method taking into account the behavioral and psychological adaptation of the occupants for the particular environment. This approach seems effective in semi-outdoor spaces designed for arbitrary occupancy where occupants seek environments different from indoors. Difference in seasonal thermal comfort condition could not be derived from the present study, and further investigation would be required in that respect.

Although only minor difference was found for predicted and observed neutral temperatures based on year-round observations, occupants in semi-outdoor spaces were found to have a wider tolerance against environmental conditions. It should be noted that the acceptability range was derived based on votes of occupants who were present at site, and votes of those who chose not to stay were excluded. However, percentage of occupants choosing not to stay can be estimated from the linear relationship between occupancy conditions and outdoor air temperature. If the objective of a particular semi-outdoor environment was to retain a certain number of people, the above relationship should be taken into account.

Behavioural adaptation in the form of clothing adjustments and selection of occupancy conditions was found to be a function of outdoor temperature in these spaces. Knowledge on what kind of environmental condition to expect would afford the occupants with a greater degree of behavioural and psychological adaptation. Environmental labelling is considered to be effective in the design stage. Abundant adaptive opportunity is another key to enhance satisfaction in a given situation. For designing comfortable thermal environment in semi-outdoor environments for arbitrary occupancy, control of environmental variable should not be aimed, but preparation of diverse occupancy environments created by such techniques as shades and windshields would likely to realize high comfort ratings by the occupants.

5.4 CONCLUSION

Thermal comfort conditions in 4 semi-outdoor spaces with different levels of environmental control were investigated from the viewpoint of short-term occupancy. Investigation of occupancy conditions, thermal environment, and occupant responses were integrated in the seasonal survey design conducted for a total of 64 days. The following conclusions were drawn.

1) Over 80% of occupants described the purpose of their stay to be voluntary activities, suggesting that their occupancy in semi-outdoor environments were arbitrary.

2) Average occupancy period was approximately 11 minutes for non-HVAC buildings and 19 minutes for HVAC buildings.

3) In non-HVAC buildings, occupancy conditions, defined in terms of number of occupants and average occupancy period, showed a linear relationship with mean outdoor temperature of the day. Decrease in outdoor temperature resulted in decrease in number and occupancy period. No link was found for occupancy conditions in HVAC buildings.

4) Daily mean clothing insulation was found to be a linear function of outdoor air temperature of the day in both HVAC buildings and non-HVAC buildings.

5) SET* was confirmed to be the best predictor of observed thermal sensation votes in semi-outdoor environments, due to the wide range of environmental parameters observed.

6) PMV was able to predict the neutral temperature of HVAC buildings based on year-round observation. Discrepancy of 1.5 °C was found for non-HVAC buildings. The predicted gradient of thermal sensation change was 1.5 times greater than that observed.

7) Occupants in semi-outdoor environments were more tolerant against a wider range of environmental conditions compared to that predicted by PPD. Eighty percent acceptability range of 17.9 °C and 9.7 °C was confirmed for non-HVAC and HVAC buildings respectively, as opposed to 4.9 °C of PPD.

CHAPTER 6

CONCLUSIVE SUMMARY

CHAPTER 6 CONCLUSIVE SUMMARY

Atria or terraces designed to introduce natural outdoor elements such as sunlight and fresh air are built in modern architecture to attract people from aesthetic aspects or to add diversity to the architectural environments. These moderately controlled semi-outdoor environments offer the occupants with the amenity of naturalness within an artificial environment, a temporal refuge from tightly controlled indoor working environment, and a thermal buffer to mitigate the large environmental step change during a transition from indoor to outdoor. Planning of the semi-outdoor environments is distinct in a way that comfort should be achieved without deteriorating the benefits of natural outdoor elements. In this thesis, the thermal comfort conditions of semi-outdoor environment were evaluated from the two primary design requirements in modern architecture, a passage space and a short-term occupancy space.

In Chapter 1, the definition of semi-outdoor environment was given, and the outline of this thesis was described. Semi-outdoor environment was defined as "an architectural environment designed to introduce natural outdoor elements with the aid of environmental control". Semi-outdoor environment falls in between the indoor environment where thermal environment is controlled to satisfy the thermal comfort of the occupants, and the outdoor environment where occupants need to adjust themselves to achieve thermal comfort. Existing thermal comfort criteria are based on steady-state comfort models such as PMV (Predicted Mean Vote) and ET* (the New Effective Temperature) designed to evaluate the thermal comfort of occupants staying in the given thermal environment for more than an hour. Thermal comfort conditions in semi-outdoor environment should be investigated with respect to how they are actually used, from the transition phase and the short-term occupancy phase.

While passing through different spaces, people experience continuous environmental step changes in a short amount of time. The heat exchange between man and the environment would not reach steady state during that period, and transient thermal conditions need to be considered for the evaluation of transition phase through semi-outdoor environments. Adaptation, the potential ability of the occupants to achieve comfort themselves, also needs to be recognized to evaluate thermal comfort under short short-term occupancy conditions.

In Chapter 2, the effect of semi-outdoor space as a thermal buffer for transition from outdoor to indoor was evaluated from the viewpoint of transient thermal comfort by physiological simulation of a passer-by. The numerical thermoregulation model based on the Stolwijk model, 65MN, was developed to simulate the heat exchange and the physiological state of the human body under transient conditions. The model consists of 16 body segments corresponding to a thermal manikin, and each consists of 4 layers for core, muscle, fat and skin. Environmental data collected from the field surveys were used as boundary conditions for the simulation of an imaginary passer-by. Seasonal surveys were conducted in an integrated public facility for summer, autumn of 1997 and winter of 1998. Assuming several imaginary routes of a visitor through an atrium, environmental measurements were conducted for the representative points along the routes. Mobile measurement cart with the capability of recording air temperature, globe temperature, relative humidity, and air velocity at four specific heights around a walking person was developed for the purpose. Numerical simulations were conducted for routes with and without an atrium along the way. It was confirmed that the presence of semi-outdoor environment as a buffer space mitigated the rate of mean skin temperature change after entrance from outdoor, especially when the temperature difference was large between indoor and outdoor.

In Chapter 3, subjective experiments were conducted to investigate the influence of environmental conditions of a buffer zone on thermal comfort in a succeeding environment. Transient thermal comfort votes and their relation to physiological variables were examined. Subjective experiments were conducted in a climate chamber divided into 3 spaces whose environmental conditions were controlled to represent an indoor space, a buffer space and an outdoor space. Air temperature of indoor space was kept at 25 °C to represent an office environment. Outdoor space was controlled at 32 °C, 70% rh for summer outdoor conditions. Environmental conditions of the buffer space were altered from the combination of 22, 25, 28 °C air temperature and 0, 3, 5, 10 minute of transition period. After 1-hour occupancy in the indoor space, subjects dressed in office work attire walked through the buffer space to the outdoor space, and returned through the same process after a 15 minute walk in the outdoor space. Two separate scales of thermal sensation, the environmental temperature sensation vote (ESV) and the whole body thermal sensation vote (TSV), were employed for subjective evaluation of thermal comfort during step changes. Environmental conditions of buffer space were found to have a minor influence on ESV, TSV, and CSV in post-transition indoor space after 40 minutes. On the other hand, a clear impact on physiological variables such as mean skin temperature and vapor pressure inside clothing was confirmed. Mean skin temperature and vapor pressure inside clothing were higher when the air temperature of buffer space was higher and the transition time was longer. However, the effects were not significant for psychological variables except for the first ESV upon entering the post-transition indoor space. Environmental conditions of buffer space were found to be irrelevant in the succeeding environment when evaluated for occupancy periods longer than 30 minutes.

In Chapter 4, field surveys were conducted to investigate the thermal comfort conditions in an office environment where the adaptive opportunity was limited compared to semi-outdoor environment. An office located in Tokyo with multi-national workers was selected to conduct 4 seasonal surveys from summer to spring, integrating questionnaire surveys and physical measurements for thermal environment and indoor air quality. A large amount of heat generating office equipments and free access of occupants to the room temperature control resulted in an air temperature difference up to 4.6 °C among the same working floor. Out of 406 returned questionnaires throughout the survey, only 26% of workers reported their working environment to be "comfortable", and only 26% voted their thermal environment to be "neutral". A significant neutral temperature difference of 3.1 °C was observed between the Japanese female occupant group and the non-Japanese male group. Differences in clothing, the type of work and the expectation for the room temperature based on their national backgrounds were suspected to be the cause of the deviation. The comfort votes and the reported frequency of SBS related symptoms were closely related to the deviation of thermal sensation vote from neutral. The thermal environment was found to be the major factor affecting occupant comfort. Occupants in the present office were relying on the adjustment of thermal environment to achieve thermal comfort, and the differences in the perception of the indoor environment were found to be negatively affecting the ratings of their working environment.

In Chapter 5, seasonal surveys were conducted in semi-outdoor architectural environments to investigate the thermal comfort characteristics and the thermal comfort conditions, taking into account the adaptation of occupants. Four semi-outdoor architectural environments with different levels of environmental control were selected for the survey in Tokyo, Japan, two of which were air-conditioned atria and two of which were non air-conditioned spaces. Buildings were selected to have a common basic feature; large-scale precincts open to public, designed for roaming and resting of the visitors. Field surveys were designed to examine the following factors: 1) the actual occupancy conditions, 2) the thermal environment, 3) the behavioral adaptation of occupants to a given thermal environment, and 4) the psychological response. Observation on the purpose of occupancy showed that the majority of activities in the semi-outdoor environments were arbitrary, and that the occupants were free to choose their own occupancy conditions. Average occupancy period in non air-conditioned buildings was approximately 10 minutes, while the values ranged from 15 to 20 minutes in air-conditioned buildings. A strong linear relationship was confirmed between the occupancy conditions and the daily mean air temperature of the survey area in non air-conditioned buildings. The number of occupants and the time of occupancy decreased following the air temperature decrease. Occupancy conditions in air-conditioned buildings showed no relation with the thermal environment. The clothing insulation of the occupants was found to correlate linearly with mean daily outdoor air temperature on yearly observation, both in air-conditioned and non air-conditioned buildings. When observed separately for each season, clothing change against air temperature change was greater in autumn and winter when daily air temperature fluctuation was greater compared to summer and spring. Of all the measured thermal variables and thermal indices calculated from these data, SET* achieved the highest correlation with the thermal sensation vote of occupants. Most of the field studies in offices employ operative temperature as the predictor of thermal sensation, but a more complex index was appropriate for a wider range of environmental parameters observed in semi-outdoor environments. Neutral temperature was calculated for both types of buildings from the linear regression equation of SET* and the mean thermal sensation vote. The neutral temperature predicted by PMV and the values derived from the actual votes were nearly equal at 25.8 °C in air-conditioned buildings. Similar neutral temperature of 25.5 °C was predicted for non air-conditioned buildings, but observed value was 1.5 °C lower. Temperature shift of 3.5 °C would equal to 1 scale unit change of the predicted thermal sensation, while it would require approximately 6 °C for the actual change. Occupants in semi-outdoor environments were more tolerant of a wider range of environmental conditions compared to that predicted by PPD (Predicted Percentage of Dissatisfied). Eighty percent acceptability range of 17.9 °C and 9.7 °C was confirmed for non air-conditioned and air-conditioned buildings respectively, as opposed to 4.9 °C of PPD.

Thermal conditions of semi-outdoor environment were confirmed to cast a prominent influence on physiological parameters of a person passing through. However, psychological effects in the succeeding environment were negligible 30 minutes after transition. If the objective of the semi-outdoor environment was to alleviate environmental step changes from indoor to outdoor, and immediate psychological response upon entrance was not of concern, the thermal environment should be designed for occupancy purposes.

Occupants of an office environment, limited with the adaptive opportunity, were mainly relying on the adjustment of thermal environment to achieve comfort, and were found to rate the comfort conditions more severely than the comfort range predicted by the thermal comfort index. On the other hand, occupants in semi-outdoor environments designed for arbitrary occupancy were able to achieve comfort in the range 2 to 3.5 times wider than that predicted by the thermal comfort index.

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NOMENCLATURE

i	= subscript for segment number (1-16)
j	= subscript for layer number (1-4)
k	= subscript for direction of radiometer (up, down, left, right, forward, back)
*65MNSET**	= SET* calculated by the 65MN model [°C]
a	= Short wave absorptance [-]
A_{Du}	= surface area of whole body [m^2]
$A_{Du}(i)$	= surface area of segment *i* [m^2]
A_{eff}	= Effective radiation area factor [-]
$B(i,j)$	= heat exchange rate between central blood compartment and node(*i,j*) [W]
$BF(i,j)$	= blood flow rate [L/h]
$BFB(i,j)$	= basal blood flow rate [L/h]
C	= heat loss by convection [W/m^2]
$C(i,j)$	= heat capacity [Wh/°C]
Cch	= shivering control coefficient for core layer of head segment [W/°C]
$Cd(i,j)$	= thermal conductance between node(*i,j*) and its neighbor [W/°C]
Cdl	= vasodilation control coefficient for core layer of head segment [L/h°C]
$Ch(i,j)$	= shivering heat production [W]
$Chilf(i)$	= distribution coefficient of muscle layer for shivering heat production [-]
$Cld(i,j)$	= cold signal [°C]
$Clds$	= integrated cold signal [°C]
Cst	= vasoconstriction control coefficient for core layer of head segment [1/°C]
Csw	= sweat control coefficient for core layer of head segment [W/°C]
$D(i,j)$	= conductive heat exchange rate with neighboring layer [W]
DL	= vasodilation signal [L/h]
E	= heat loss by evaporation [W/m^2]
$E(i,4)$	= evaporative heat loss at skin surface [W]
$E_b(i,4)$	= heat loss by water vapor diffusion through skin [W]
$E_{max}(i)$	= maximum evaporative heat loss [W]
$E_{sw}(i,4)$	= heat loss by evaporation of sweat at skin layer [W]
$Err(i,j)$	= error signal [°C]

$F(i,j)$ = temperature change rate [°C /h]

$I_{cl}(i)$ = clothing insulation [clo]

$I_{dif,k}$ = Diffuse solar radiation for each direction [W/m^2].

$I_{dir,k}$ = Direct solar radiation for each direction [W/m^2]

$I_{dir,n}$ = Solar radiation normal to the sunray for each direction [W/m^2]

$I_{net,k}$ = Net solar radiation for each direction [W/m^2]

K = heat loss by conduction [W/m^2]

L_k = Net long wave radiation for each direction [W/m^2]

LR = Lewis ratio [°C /kPa]

M = metabolic rate [W/m^2]

$Metf(I)$ = distribution coefficient of muscle layer for heat production by external work [-]

MRT = Mean radiant temperature [°C]

Pch = shivering control coefficient for core layer of head segment and skin layer of each segment [W/°C ^{2}]

Pdl = vasodilation control coefficient for core layer of head segment and skin layer of each segment [L/h°C ^{2}]

Pst = vasoconstriction control coefficient for core layer of head segment and skin layer of each segment [1/°C ^{2}]

Psw = sweat control coefficient for signals from core layer of head segment and skin layer of each segment [W/°C ^{2}]

$Q(i,j)$ = rate of heat production [W]

Q_b = basal metabolic rate of whole body [met]

$Q_b(i,j)$ = basal metabolic rate [W]

$Q_t(i,4)$ = convective and radiant heat exchange rate between skin surface and environment [W]

R = heat loss by radiation [W/m^2]

$RATE(i,j)$ = dynamic sensitivity of thermoreceptor [h]

RES = heat loss by respiration [W/m^2]

$RES(2,1)$ = heat loss by respiration at core layer of chest segment [W]

$RT(i,4)$ = temperature width required for $km(i,4)$ to be 2 [°C]

Sch = shivering control coefficient for skin layer of each segment [W/°C]

Sdl = vasodilation control coefficient for skin layer of each segment [L/h°C]

SKINC(i = distribution coefficient of skin layer for ST [-]

SKINR(i = weighting coefficient for integration of sensor signals [-]

SKINS(i) = distribution coefficient of skin layer for sweat [-]

SKINV(i = distribution coefficient of skin layer for DL [-]

Sst = vasoconstriction control coefficient for skin layer of each segment [1/°C]

Ssw = sweat control coefficient for skin layer of each segment [W/°C]

ST = vasoconstriction signal [-]

T(65) = blood temperature in central blood compartment [°C]

T(i,j) = temperature [°C]

$T_{set}(i,j)$ = set-point temperature [°C]

W = external work [W/m^2]

W(i,j) = external work [W]

Wrm(i,j) = warm signal [°C]

Wrms = integrated warm signal [°C]

$f_{cl}(i)$ = clothing area factor [-]

$h_c(i)$ = convective heat transfer coefficient [W/m^2°C]

$h_e(i)$ = evaporative heat transfer coefficient from skin surface to the environment [W/m^{2}kPa]

$h_r(i)$ = radiant heat transfer coefficient [W/m^2°C]

$h_t(i)$ = total heat transfer coefficient from the skin surface to the environment [W/m^2°C]

$i_{cl}(i)$ = vapor permeation efficiency of clothing [-]

km(i,4) = local multiplier [-]

met = metabolic rate of whole body [met]

$p_a(1)$ = vapor pressure at head segment [kPa]

$p_a(i)$ = ambient vapor pressure [kPa]

$p_{sk,s}(i)$ = saturate vapor pressure on skin surface [kPa]

R = Net radiation [W/m^2]

R_{dif} = Net diffuse radiation [W/m^2].

$R_{dif,k}$ = Net diffuse radiation for each direction [W/m^2]

R_{dir} = Net direct radiation [W/m^2]

$R_{net,k}$ = Net radiation (long wave and solar) for each direction [W/m^2]

$t_a(1)$ = air temperature at head segment [°C]

$t_o(i)$ = operative temperature [°C]

α = ratio of counter current heat exchange [-]

γ_p = Irradiated area as fraction of Dubois area [-]

ρC = volumetric specific heat of blood [Wh/L°C]

σ = Stefan Boltzmann constant (5.67 x 10^{-8} [W/m^{2}K^4]).

APPENDIX

Original Questionnaires in Japanese

1．あなたはこの**室内の熱環境**をどう感じますか？

-3	-2	-1	0	+1	+2	+3
寒い	涼しい	やや涼しい	どちらでもない	やや暖かい	暖かい	暑い

2．**あなた自身**はいまどう感じてますか？

-3	-2	-1	0	+1	+2	+3
寒い	涼しい	やや涼しい	どちらでもない	やや暖かい	暖かい	暑い

3．あなたはこの**室内の環境**を快適だと思いますか？不快だと思いますか？

-3	-2	-1	0	+1	+2	+3
非常に不快	不快	やや不快	どちらでもない	やや快適	快適	非常に快適

4.あなたは現在、**汗**をかいていますか？

0	+1	+2	+3
汗をかいていない	やや汗をかいている	汗をかいている	非常に汗をかいている

5．あなたは**汗による着衣の状態**を受け入れられますか？受け入れられませんか？

-1		0		+1
受け入れられない	どちらかというと受け入れられない		どちらかというと受け入れられる	受け入れられる

6．あなたはどの部分が**汗により濡れている**と感じていますか？（複数可）

無し　腹　首　胸　背中　脇の下　大腿　膝裏　その他（　　　　）

7．あなたはこの**室内の熱環境**を受け入れられますか？受け入れられませんか？

-1		0		+1
受け入れられない	どちらかというと受け入れられない		どちらかというと受け入れられる	受け入れられる

半屋外環境に関するアンケート調査

Survey Number ＿＿＿＿＿＿

早稲田大学理工学部建築学科田辺研究室

基本的事項についてボックスにチェックを入れるか、必要事項を記入して下さい。

① 性別、年齢をお聞かせください。

□男性 □女性

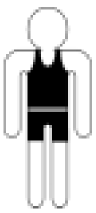
□20 才未満 □20-29 才 □30-39 才 □40-49 才 □50-59 才 □60-69 才 □70 才以上

② 職業をお聞かせください。

□会社員 □自営業 □専業主婦 □パート/アルバイト □学生 □その他 ( )

③ あなたが今着用している衣服の組み合わせについてボックスにチェックをつけて下さい。

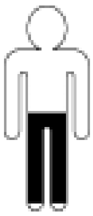
肌着



肌着	長袖	半袖	袖なし
□肌着 (上)	[□	□	□]
□靴下			
□ストッキング			
□腹巻き			

	膝上	膝丈	膝下
□タイツ			
□肌着 (下) (下着以外)	[□	□	□]

下半身



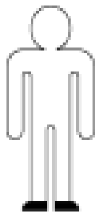
下半身	薄	厚
ズボン・パンツ	[□	□]

	膝上	膝丈	膝下
ズボン・パンツ	[□	□	□]

下半身	薄	厚
スカート	[□	□]

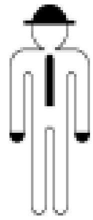
	膝上	膝丈	膝下
スカート	[□	□	□]

靴類



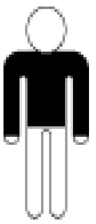
□革靴
□スニーカー
□サンダル
□ショートブーツ
□ロングブーツ

小物類



□ネクタイ
□帽子
□マフラー
□ストール
□スカーフ
□手袋
□耳あて
□カイロ

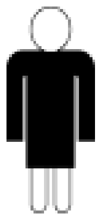
上半身



上半身	長袖	半袖	袖なし	薄	厚
襟付きシャツ (Yシャツ/ブラウス類)	[□	□	□]	[□	□]
シャツ (Tシャツ/ポロシャツ類)	[□	□	□]	[□	□]
その他シャツ (タートル/ニット類)	[□	□	□]	[□	□]
ワンピース	[□	□	□]	[□	□]

	長袖	半袖	袖なし	薄	厚
ベスト	[		□]	[□	□]
セーター	[□	□	□]	[□	□]
トレーナー (パーカー/フリース類含む)	[□	□	□]	[□	□]
カーディガン	[□	□	□]	[□	□]
タートルネック セーター	[□	□	□]	[□	□]
ジャケット	[□	□	□]	[□	□]

コート類



コート類	薄	厚
ロングコート	[□	□]
ハーフコート	[□	□]
ジャンパー	[□	□]
ウィンドブレーカ	[□	□]
ダウンジャケット	[□	□]
トレンチコート	[□	□]

④ あなたが現在座っている場所の利用目的は何ですか？

□休憩 □食事 □待ち合わせ □読書 □パソコン □喫煙 □電話/メール □談話 □その他 (＿＿＿＿)

⑤ あなたは今汗をかいていますか？

□かいていない □ややかいている □かいている □非常にかいている

⑥ あなたはどのくらいここにいましたか？

□5 分未満 □5～10 分 □10～15 分 □15 分以上

⑦ あなたはここでなにをしていましたか？

□休憩 □食事 □待ち合わせ □読書 □パソコン □喫煙 □電話/メール □談話 □その他 (＿＿＿＿)

⑧ あなたは 15 分前、なにをしていましたか？

□仕事・授業 (屋内) □仕事・授業 (屋外) □食事 □買物 □散歩

□運動 □ここにいた □歩いて移動 □乗り物で移動 □その他 (＿＿＿＿＿＿＿＿＿＿)

⑨ あなたの現在の健康状態はどうですか？

□良い □普通 □あまり良くない □悪い

⑩ ここ 2 時間の間にお酒を飲みましたか？

□飲んだ □飲んでいない

⑪ あなたは今日の天気予報を知っていますか？

□はい □いいえ

⑫ この場所に来るのは何回目ですか？

□初めて □5 回以下 □10 回以下 □それ以上

▼裏面へ

あなたが現在座っている場所の環境について、ボックスにチェックを入れるか、必要事項を記入してください。

⑬-1　あなたが今座っている環境は快適ですか、不快ですか？

□非常に快適	□快適	□やや快適	□どちらでもない	□やや不快	□不快	□非常に不快
+3	+2	+1	0	-1	-2	-3

⑬-2　⑬-1で「非常に快適」「快適」「やや快適」と答えた方にお聞きします。快適と感じる要因は何だと思いますか？
(複数回答可)　(上記以外で答えた方は結構です。)

□温度　□植栽　□太陽の光　□喫煙可　□湿度　□風　□開放感　□音　□香り・匂い　□他の人の存在
□空間の大きさ　□空間の明るさ　□座れる・休める空間　□その他（　　　　　　　　）

⑬-3　⑬-1で「やや不快」「不快」「非常に不快」と答えた方にお聞きします。不快と感じる要因は何だと思いますか？
(複数回答可)　(上記以外で答えた方は結構です。)

□温度　□植栽　□太陽の光　□喫煙可　□湿度　□風　□開放感　□音　□香り・匂い　□他の人の存在
□空間の大きさ　□空間の明るさ　□座れる・休める空間　□その他（　　　　　　　　）

⑭　あなたは今この場所をどう感じますか？

□暑い	□暖かい	□やや暖かい	□どちらでもない	□やや涼しい	□涼しい	□寒い
+3	+2	+1	0	-1	-2	-3

⑮　あなたはこの場所の温度がどうあればよいと思いますか？

□今より暖かい方がよい　□このままでよい　□今より涼しい方がよい

⑯-1　あなたは今この場所で気流（風）を感じますか？

□はい　□いいえ

⑯-2　あなたはこの場所の気流がどうあればよいと思いますか？

□今より強い方がよい　□このままでよい　□今より弱い方がよい

⑰-1　あなたは今この場所の湿度をどう感じますか？

□非常に湿っている　□湿っている　□どちらでもない　□乾いている　□非常に乾いている

⑰-2　この場所の湿度がどうあればよいと思いますか？

□今より高い方がよい　□このままでよい　□今より低い方がよい

⑱-1　あなたは今この場所で日射（ぽかぽか、じりじり等）を感じますか？

□はい　□いいえ

⑱-2　この場所の日射がどうあればよいと思いますか？

□今より強い方がよい　□このままでよい　□今より弱い方がよい

⑲　あなたが今座っている場所の「暑さ・寒さ」を受け入れられますか？受け入れられませんか？

□受け入れられる　□受け入れられない

⑳　この場所について感じること、望むことなどがあればお書きください。

おつかれさまでした。

アンケート調査にご協力いただきまして、ありがとうございました。