Thermal comfort conditions in semi-outdoor environments for short-term occupancy

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ABSTRACT
A series of seasonal field surveys integrating thermal environment measurement around the occupant, questionnaire survey, and occupant observation was conducted from summer of 2001 to spring of 2002 in order to investigate the thermal comfort conditions in semi-outdoor environments from the viewpoint of short-term occupancy. A total of 2248 questionnaires and corresponding sets of environmental data were collected. Majority of occupants were engaged in arbitrary activities, and their occupancy period was much shorter than general indoor occupancy period. SET* was confirmed to be the best predictor of observed thermal sensation votes. Though neutral temperature was found to vary from season to season, consistent climatic dependency could not be observed from the present results. Occupants in semi-outdoor environments were tolerant of twice to thrice wider range of environmental conditions compared to that predicted by PPD, suggesting that thermal comfort condition differs from that of indoor steady state.

INDEX TERMS
Thermal comfort; Field survey; Semi-outdoor environment

INTRODUCTION
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 and function as a temporal refuge from tightly controlled indoor thermal environment. Planning of the semi-outdoor environments is distinct in a way that comfort should be achieved without deteriorating the benefits of natural outdoor elements. Although little work has been done on thermal comfort in such environments, it is likely that people expect environments differing from indoors, and the thermal comfort condition may differ from that of indoor steady state. In order to investigate the thermal comfort conditions in the semi-outdoor spaces from the viewpoint of short-term occupancy, architectural environments with different levels of environmental control were selected. Results of the four seasonal field surveys carried out from summer of 2001 to spring of 2002 are reported in this paper.

METHODS
Four semi-outdoor architectural environments located in Tokyo, Japan, were selected for the survey, two of which were air-conditioned atria (HVAC spaces) and two of which were non-air conditioned spaces (non-HVAC spaces), designed for roaming and resting of the visitors. The details of the survey area are listed in Table 1. Surveys from 10:00 to 18:00 each day were conducted for 4 days per space per season for four seasons, adding up to a total of 64 days. A short-term occupant was defined as the visitor who actually sat

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Table 1 Description of the survey areas

					
Building	O		T	P	B
Description	office + shopping mall		departmenmt store	office + shopping mall	office + shopping mall
Survey area	arcade	sunken garden	wooden deck	closed atrium	closed atrium
Floor area x Height	830 m^2 x 16 m	650 m^2 no roof	1,500 m^2 no roof	1,600 m^2 x 18 m	4,200 m^2 x 40 m
HVAC	non		non	all year	all year

Table 2 Measurement items

	Measurement items	Instruments	Height (m)
Occupied zone	Air temperature	C-C thermocouples	0.1 / 0.6 / 1.1 / 1.7
	Air velocity	Heated anemometer	0.1 / 0.6 / 1.1 / 1.7
	Humidity	RH sensor	0.1 / 1.1
	Total radiation	Directional radiometer (0.3-4.0μm)	1.1 (6 sides)
	Solar radiation	Silicon pyranometer (0.4-1.1μm)	1.1 (6 sides)
	Surface temperature	C-C thermocouples	Seat + ground
Outdoor conditions	Air temperature	Thermister	
	Humidity	RH sensor	
	Solar radiation	Solar meter	

down in the survey area, and a passer-by or a standing person was left out of scope from the present survey.

A questionnaire survey with simultaneous measurement of thermal environment around the respondent was conducted for the thermal comfort survey. A questionnaire sheet included questions concerning approximate length of stay, activity within 15 min, clothing items, general comfort (seven scales, very comfortable to very uncomfortable), thermal sensation (ASHRAE scale), thermal preference (McIntyre scale) and thermal acceptability. Details of sex, age, purpose of stay and health condition were also asked for background information. A mobile measurement cart equipped with batteries for a full day operation was devised to measure the thermal environment around the respondent. Measurement items are given in Table 2. The radiant environment was evaluated by measuring the directional total radiation (0.3–4.0 μm) and solar radiation (0.4–1.1 μm) separately for six directions (up, down, front, back, left, right) at 1.1 m above floor level. Calculation of MRT is described in a previous paper (Nakano *et al.*, 2002). After obtaining the consent of an occupant to answer the questionnaire, another surveyor drove the cart near the respondent to measure the immediate environment for 10 min. Average value of the last 3 min was used for analysis. A total of 2248 questionnaires and corresponding environmental data were collected throughout the survey. Outdoor conditions were recorded separately at a representative point. Observation of occupancy period and number of occupants in the area was also included in the survey, but the details are discussed elsewhere (Nakano *et al.*, 2003).

RESULTS

Occupancy Conditions

Percentage of males to females was equal in non-HVAC spaces while 60% were females in HVAC spaces. More than 80% of entire occupants were engaged in arbitrary activities such as resting and eating, implying that most of the occupants were free to stay or leave at their will.

The yearly average occupancy period was found to be 18 min in HVAC spaces and 10 min in non-HVAC spaces, much shorter than the general indoor occupancy period.

Thermal Environment

Thermal environmental characteristics of the occupied zone were analysed according to the two environmental classifications. Relationship between outdoor air temperatures and air temperatures of the occupied zone measured around the questionnaire respondent with the mobile measurement cart are given in Figure 1(a). Air temperature closely coincided with the outdoor temperature in non-HVAC spaces. Links between the two temperatures were also observed in HVAC spaces, but the occupied zone was generally kept between 15 and 29°C by air conditioning. Mean radiant temperatures (MRT) of the occupied zone are plotted against air temperature of the occupied zone in Figure 1(b). MRT close to air temperature was observed in HVAC spaces while prominently higher values were recorded in non-HVAC spaces due to solar radiation. The humidity ratio of occupied zone and outdoor is presented in Figure 1(c). Mild humidity control was confirmed in HVAC spaces, especially when outdoor humidity was high. Relative frequency of air velocity observed within the occupied zone is shown in Figure 1(d). Majority of mean air velocity measured in HVAC spaces 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 spaces.

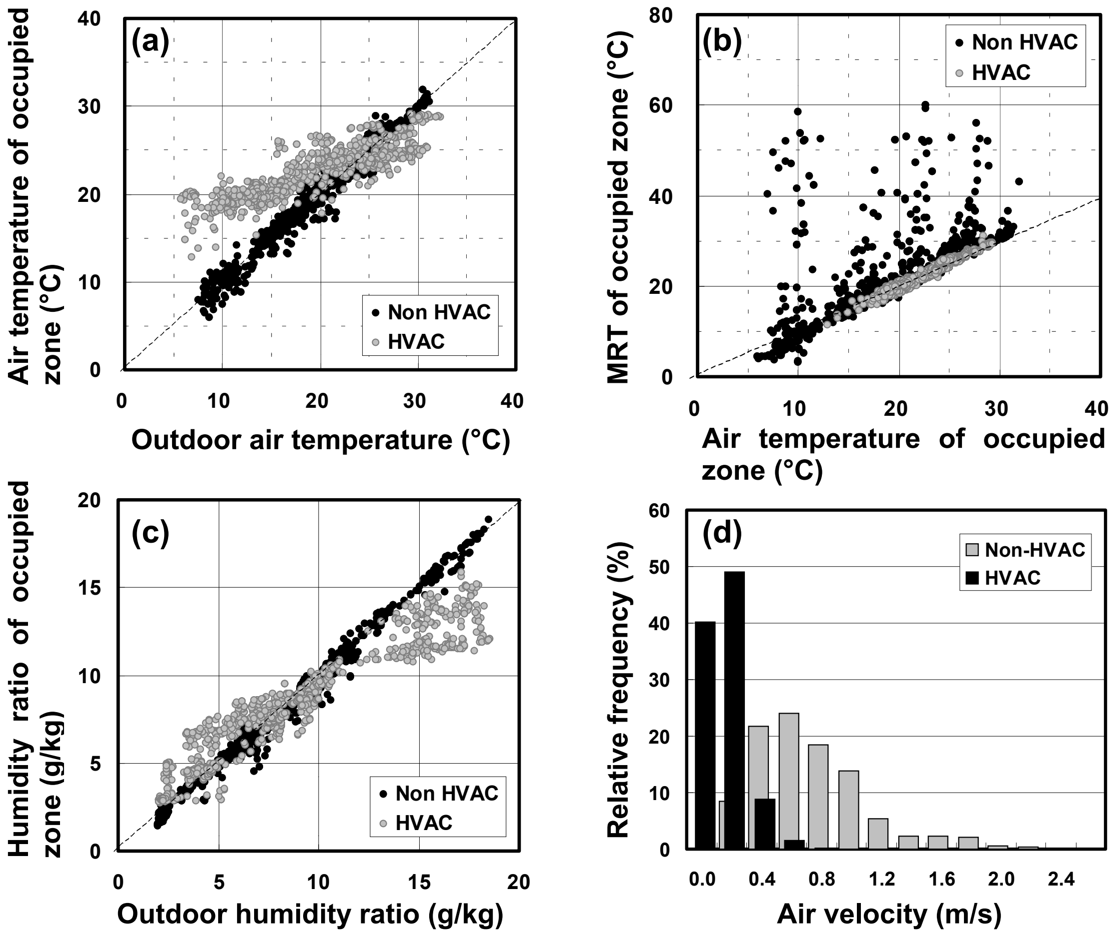

Figure 1 Environmental characteristics of HVAC spaces and non-HVAC spaces.

Neutral Temperature

PMV, SET*, ET* and operative temperature were calculated for each respondent from the immediate environmental variables recorded by the mobile measurement cart. Clothing insulation was estimated by integrating the two garment checklists marked separately by the respondent and the surveyor to avoid any apparent fill-in errors. Each clothing item was assigned an insulation value (ISO 9920, 1995) and summed for total insulation. Occupants sitting in the cushioned lounge chair of space P were added 0.15 clo for insulation of the chair. No increase was considered for occupants in other spaces sitting on wooden or metal meshed benches, assuming that a slight increase was compensated by the decrease of boundary air layer (McCullough *et al.*, 1994). As all the occupants were seated at the time of questionnaire, estimation of metabolic rate was difficult due to lack of information on transient influence of precedent activity. Metabolic rate was assumed to be 1.1 met for all respondents, a value slightly higher than sedentary seated condition, instead of applying numerous assumptions. SET* achieved the highest correlation with observed thermal sensation votes as opposed to operative temperature adopted by various field studies in office. 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 four 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 was applied to each seasonal observation and the neutral temperature (T_n) for the mean thermal sensation vote of 0 was calculated. The results are presented in Table 3. Neutral temperatures were higher in HVAC spaces than in non-HVAC spaces throughout the year, with the maximum difference of 3.5°C in winter and minimum of 1.2°C in summer.

Table 3 Seasonal neutral temperature and linear fit equation for SET* and TSV

	Season	Tn (°C)	Linear fit equation	r^2
Non-HVAC	Summer	24.4	TSV = 0.2418 x SET* - 5.8992	0.93
	Autumn	23.4	TSV = 0.2078 x SET* - 4.8663	0.80
	Winter	24.9	TSV = 0.1357 x SET* - 3.3848	0.65
	Spring	23.9	TSV = 0.1741 x SET* - 4.1687	0.83
HVAC	Summer	25.6	TSV = 0.2527 x SET* - 6.4598	0.81
	Autumn	25.6	TSV = 0.1789 x SET* - 4.5770	0.89
	Winter	28.4	TSV = 0.0930 x SET* - 2.6434	0.36
	Spring	26.3	TSV = 0.1396 x SET* - 3.6702	0.82

Thermal Comfort Conditions

Existing thermal comfort criteria 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 space. Therefore, an alternative relationship was sought among comfort condition and thermal environment. General comfort sensation vote, not confined to thermal aspects, was included in the questionnaire. A seven-point scale of comfort was categorized into three classes of ‘comfort (very comfortable, slightly comfortable, comfortable)’, ‘neutral’ and ‘discomfort (very uncomfortable, slightly uncomfortable, uncomfortable)’. The ‘comfort’ and ‘neutral’ ranges were not dependent on thermal aspects, and other factors of semi-outdoor environment such as visual aspects are assumed 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 2. The PPD curve calculated for the standard condition of SET* ($t_a = t_r$, $v = 0.1$ m/s, rh = 50%, 0.6 clo, 1 met) was added to illustrate the difference in the comfort range.

The discomfort curves were steeper in the order of PPD, HVAC and non-HVAC, implying that occupants in semi-outdoor environments were more tolerant of 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 4. The 80% acceptability range of non-HVAC spaces was approximately 18°C, three times as wide as that of PPD. The same range for HVAC spaces was twice as that of PPD.

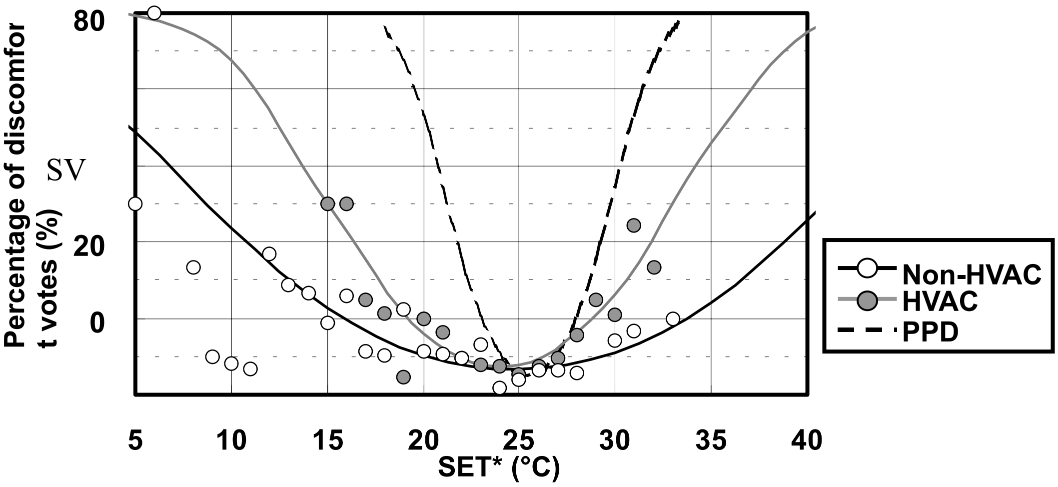

Figure 2 SET* and percentage of discomfort votes.

Table 4 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

DISCUSSION

The determination coefficients for linear fit equation of SET* and observed thermal sensation votes were lower in winter compared to other seasons, both in non-HVAC and HVAC spaces. One of the reasons is suspected to be the estimation error in clothing insulation. Estimation for a variety of coats and jackets would be less accurate with a simple checklist. The double-checking procedure by visual inspection of the surveyor would also have been less effective in winter when majority of clothing was hidden under a coat. Conscious and unconscious shivering in cold environments might have contributed to slight increase in metabolic rate, which was not recorded during the survey. In other seasons however, over 80% of mean thermal sensation could be explained by SET*.

Another method for derivation of the comfort temperature is to use thermal preference scale instead of thermal sensation scales. This approach was attempted in the present study to examine the effect on seasonal neutral temperature, but seasonal bias in preference votes prohibited this method. Only four out of 419 respondents voted that they wanted the environment to be ‘cooler’ during winter, and only 22 out of 614 voted to be ‘warmer’ during summer.

Various researchers have proposed the adaptive model of thermal comfort, which relates the indoor comfort temperature with the outdoor conditions (Humphreys and Nicol, 1998; de Dear and Brager, 2002). Comparison of present results with the proposed equations could not be conducted due to the fact that SET* was used to derive the neutral temperature in this study. Clothing adjustment was already taken into account through calculation of SET*, while the adaptive models are derived by incorporating the effects of various forms of adaptation into the relationship between outdoor temperature and indoor comfort operative temperature. Though neutral temperature was found to vary from season to season, consistent climatic dependency could not be observed from the present results. On the other hand, occupants in semi-outdoor environments were confirmed to have twice to thrice wider tolerance of thermal environment than indoors, suggesting that thermal comfort condition in semi-outdoor environments differs from that of indoor steady state.

The questionnaire survey was focused on actual occupants to examine their thermal comfort conditions. However, occupancy in the present semi-outdoor environments was confirmed to be arbitrary, and subjective votes of the occupants who chose not to stay could not be accounted for. The results presented in this paper do not necessarily apply to the entire group of visitors. On the other hand, observation on occupancy conditions was conducted separately, and dependency of daily number of occupants and occupancy period on mean daily outdoor temperature was confirmed (Nakano *et al.*, 2003). If the objective of a particular semi-outdoor environment was to retain a certain number of people within, behavioural adaptation characteristics should be taken into account, together with the results presented in this paper.

CONCLUSION

Thermal comfort conditions in four semi-outdoor spaces with different levels of environmental control were investigated from the viewpoint of short-term occupancy. A total of 2248 questionnaires and corresponding sets of the immediate environmental data were collected during 64 days of the yearly survey. Majority of occupants were engaged in arbitrary activities, and their occupancy period was much shorter than general indoor occupancy period. SET* was confirmed to be the best predictor of observed thermal sensation votes, due to the wide range of environmental parameters observed. Though neutral temperature was found to vary from season to season, consistent climatic dependency could not be observed from the present results. Occupants in semi-outdoor environments were tolerant of twice to thrice wider range of environmental conditions compared to that predicted by PPD, suggesting that thermal comfort condition differs from that of indoor steady state.

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