Adaptive Control which considers Human Comfort corresponding to Thermal Environment Change, and it's Energy Saving Effect

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ABTRACT
This paper shows the experimental evaluation of thermal comfort of people moving from outdoors to indoors in summer. It also shows a building example which makes positive use of environmental changes to improve thermal comfort in the destination, with evaluation by field experiments in summer. A performing arts center based on a Grand Hall was analyzed in this study. The visitors pass thorough several spaces as they move from the outdoor environment to the Grand Hall, and they experience several different indoor environments. In this study, effectiveness of human thermal comfort during movement from outdoors to indoors and optimization of air-conditioning control were investigated by field experiments. It shows the effect of energy saving and improvement of thermal comfort achieved by this HVAC (Heating, Ventilating and Air Conditioning) control system.

1 INTRODUCTION

With the rapid development of office automation in recent years, non-uniform thermal office environments occur with the increasing adaptation of partitioned space. It has become more difficult to ensure thermal comfort for all office workers simply by use of an air-conditioning system set to a fixed indoor temperature.
There are some widely used practical comfort standards, such as SET* (Gagge et al. 1971) and PMV (Fanger 1972). However, these are static standards, which are intended to optimize the thermal acceptability of users in a steady condition in an indoor environment. On the other hand, in the adaptive model hypothesis, people's contextual factors and past thermal history affect their thermal expectations and preferences (de Dear et al. 1997).
This paper investigates two subjects, as follows.

1.1 Evaluation of thermal comfort of persons moving from outdoors to indoors

Climatic conditions usually change when a person moves from cold or hot outdoor space to an air-conditioned indoor space. Thermal comfort also changes according to the climate change. These changes incur both physiologically and psychologically influences. Sometimes people experience different levels of thermal comfort even under the same thermal conditions.
In this study, as the first step, these changes were measured by experiments in summer. They were measured by using questionnaire survey, a mobile measurement device which analyzes the environmental conditions around the subject, and a near infrared oxygenation monitor which measures the oxygen saturation level of blood in the brain to examine the subject's physiological condition.
Results of these experiments show that real thermal comfort differs from the stationary standard, and that it is important to know the history which the person experiences.

1.2 Building example which makes positive use of environmental change to improve the thermal comfort in destination, and its evaluation by field experiments.

A performing arts center including a Grand Hall used both for opera and concerts was analyzed in this study. The visitors pass thorough several spaces including the Main Entrance, Piazza and Foyer as they move from outdoors to the Grand Hall, and they experience several different environments. In this study, effectiveness of human thermal comfort during movement from outdoors to indoors and optimization of air-conditioning control were investigated by field experiments.

2 EVALUATION OF THERMAL COMFORT OF PERSONS MOVING FROM OUTDOORS TO INDOORS

2.1 Outline

Each space on the path along which a person moves has its own thermal environment, and he/she perceives the change of thermal environment. Not only in the movement from outdoors to indoors, but also in the movement through indoor space, the air and temperature distribution changes. Perceiving the thermal change, sometimes a person feels more comfortable. However, sometimes he/she feels discomfort. To provide thermal comfort and energy saving, task-ambient air-conditioning systems and personal air-conditioning systems have been introduced in buildings. These systems use the spatial distribution positively. For appropriate HVAC control and thermal comfort, it is necessary to know the influence of thermal change on human perception both physiologically and psychologically.

In this study, human comfort was examined corresponding to the thermal environmental change by the field experiment and questionnaire survey in summer for the first step.

2.2 Method

Three kinds of spaces with different thermal environment, a cold space, a hot space, and a comfortable space respectively, were prepared (see Table 1). Five subjects, all healthy adult males, wore clothing ensembles consisting of a long-sleeved shirt, trousers and socks. All subjects wore their own underwear. The clo value was estimated to be 0.7. To keep their metabolic rate at 1.4 met, subjects were asked to walk on walking machine for 10 minutes.

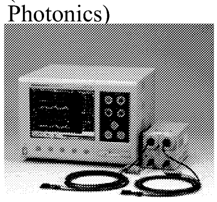
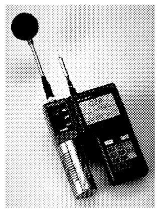
Table 2 shows the measurement items.

Cases analyzed are grouped into 3 according to the movement situation.

Table 1. Thermal condition of each space

Condition \ Space	Cold Space	Comfortable Space	Hot Space
Temperature	19-20 °C	24-26 °C	30 °C
Humidity	70%	55-60%	65%

Table 2. Measurement items

Items		Measuring instruments
Tissue oxygenation index (TOI) [1]		Tissue oxygenation monitor used near infrared spectroscopy NIRO-200 (Hamamatsu Photonics) 
Normalized tissue hemoglobin index	Concentration change in the oxygenated hemoglobin	
	Concentration change in the deoxygenated hemoglobin	
	Concentration change in the total hemoglobin	
Body temperature	Groin	NR-1000 (KEYENCE)
Skin temperature	Arm, chest, thigh	
Air temperature		101AM (Kyoto Electronics) 
Relative humidity		
Radiant temperature		
Wind velocity		
PMV, PPD		
Thermal comfort	Comfort sensation : +3 (comfort) – –3 (discomfort) Thermal sensation : +3 (hot) – –3 (cold)	Questionnaire survey

1) TOI shows the oxygen saturation level. In this study, because the correlation had been observed between the TOI and the stationary state temperature in the surrounding, TOI was used as a monitor of the temperature in the surrounding that a person felt.

1) Case 1

Measurement was conducted at each space, cold space (Cold), comfortable space (Comfort) and hot space (Hot).

2) Case 2

Measurement was conducted after the subjects moved to Comfort or Cold from Hot.

3) Case 3

Cold shock case. Measurement was conducted at Comfort after the subjects experienced the cold condition.

Table 3. Thermal comfort

Thermal comfort \ Case	Case 1			Case 2		Case 3
	Cold	Comfort	Hot	to Comfort	to Cold	Cold shock
Comfort sensation	-1.4	2.2	-0.8	1.8	0.0	2.0
Thermal sensation	-2.2	0.0	1.2	0.0	-2.2	0.0

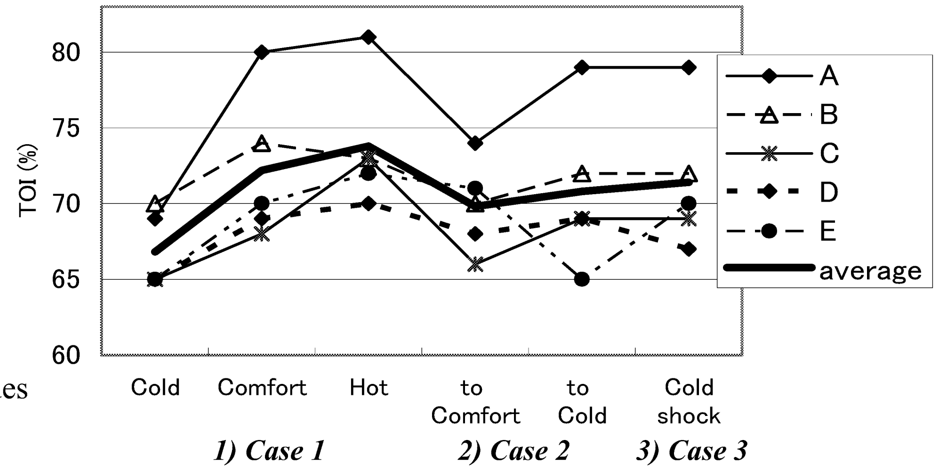


Figure 1. TOI values

2.3 Results
1) Case 1 (steady condition)
The result of thermal comfort is shown in Table 3, and the result of Tissue Oxygenation Index (TOI) is shown in Figure 1. The letters A-E mean 5 subjects. The difference of each subject's thermal comfort was small.
Concerning the thermal sensation declaration, valid results were obtained at each condition. A high TOI value was indicated in order of temperature.

2) Case 2 (moving condition from hot space)
In the movement from Hot to Comfort, average value of comfort sensation was 1.8 and thermal sensation was 0.0. These values were similar to those of Comfort steady condition (Case 1).
However, average value of TOI was 70%, which was smaller than that of Comfort steady condition, approaching the value of Cold steady condition. It means that the psychological reaction did not correspond with the physiological response.
In the movement from Hot to Cold, average value of comfort sensation was 0.0 and thermal sensation was -2.2. The subjects felt cold, however they did not feel discomfort even in cold condition. Average value of TOI was 71%, which was close to that of movement from Hot to Comfort and different from that of Cold steady condition.

3) Case 3 (moving condition which the subjects experienced the cold shock from hot space)
Average value of comfort sensation was 2.0 and thermal sensation was 0.0. These values were very similar to those for Comfort steady condition (Case 1). Average value of TOI was 71%, which was also very close to that of Comfort steady condition. In this case, the psychological reaction corresponded with the physiological response.

2.4 Conclusion of evaluation of thermal comfort of persons moving from outdoors to indoors
Thermal environmental change in pass space, human experienced, affected his thermal comfort. Sometimes, the psychological reaction did not correspond with the physiological response.
However, the appropriate change such as cold shock, may lead to the coincidence of the psychological reaction and the physiological response. There are possibilities of using these effects for energy saving.

3 BUILDING EXAMPLE WHICH MAKES POSITIVE USE OF ENVIRONMENTAL CHANGE TO IMPROVE THERMAL COMFORT IN DESTINATION, AND ITS EVALUATION BY FIELD EXPERIMENTS

3.1 Outline

This performing arts center, which opened in 2005, has three state-of-the-art halls - the Grand Hall (2,001 seats), the Theater (800 seats), and the Recital Hall (417 seats) - capable of accommodating concerts, operas, ballets, plays and various other performing arts events (see Figure 2). Most visitors walk from the station on the Pedestrian Deck, then enter the Main Entrance, passing through the Piazza to reach the Grand Hall. The piazza has a light ceiling using natural sunlight like an atrium. It was designed for visitors to use as an intersection of the traffic line to three halls and as space in which to stay for a while, providing information of concerts, operas, ballets, plays and other performing arts.

Thermal sensations according to the movement were measured for the Grand Hall. While the room temperature, the illuminance, and residence time etc. of path space from outdoor to the hall were changed, a questionnaire survey was conducted and the influence of thermal sensation on the human body was investigated.

3.2 Method

Measurements were conducted on August 22-25, 2006. The change of the thermal environment and other factors from outdoors to the Grand Hall, and its influence on the human body were focused on in this study.

Measurement item and outline of measuring instrument are shown in Table 2.

Mobile measurement apparatus for measuring the environment around subjects was set up for this experiment. It consisted of a mobile measurement cart and the measurement items shown in Table 2. Using this system, transient thermal environment and other factors around the subject walking to the Grand Hall were measured in summer. The questionnaire survey and the measurement of body and skin temperature were also conducted. Just after the subject reached the Grand Hall, the Tissue Oxygenation Index (TOI) etc. were measured by tissue oxygenation monitor using near infrared spectroscopy to assess the subject's physiological condition.

In the adaptation group (Cases 1.1-1.3), whenever a subject passed through the room, the temperature gradually fell. In the cold shock group (Cases 2.1-2.3), subjects experienced the cold environment before entering the Grand Hall. In each group (Cases 1.1-2.3), residence time in passing through the room between outside and the Hall was set as the parameter of the experiment.

Firstly, subjects walked around at the Pedestrian Deck for 10 minutes to keep their metabolic rate at 1.4 met. Then they stayed in each area for the time shown in Table 4. Finally, they entered the Grand Hall.

The 5 subjects were healthy adult males, and wore clothing ensembles consisting of long-sleeved shirt, trousers and socks. All subjects wore their own underwear. The clo value was

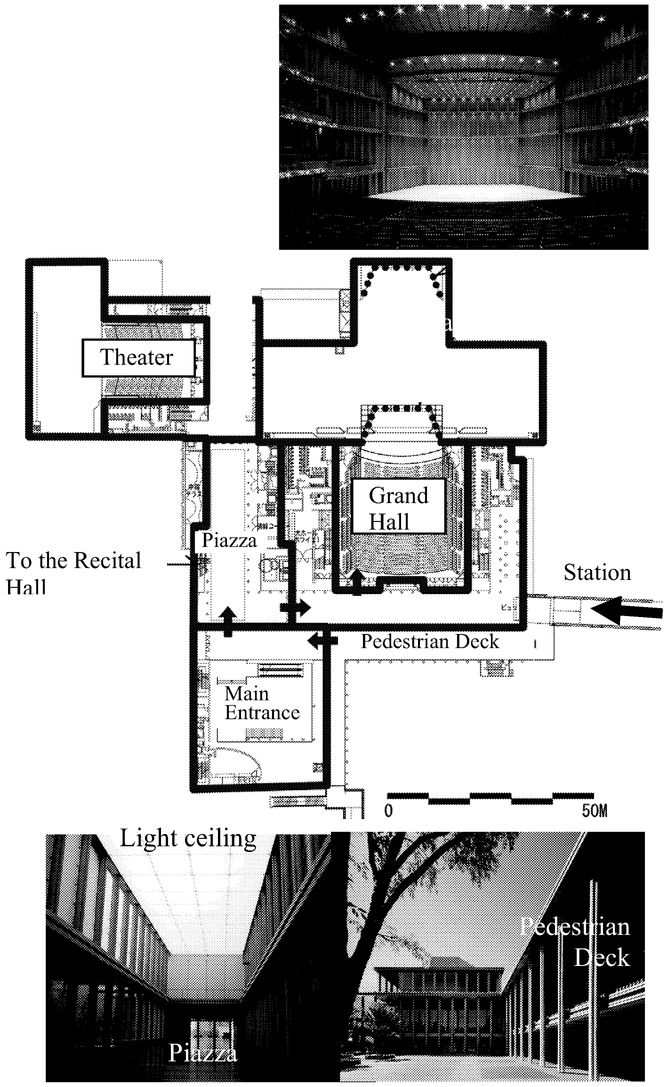


Figure 2. The performing arts center

Table 4. Measurement cases analyzed

		Pedestrian deck	Main Entrance	Piazza	Grand Hall
Case	Outline Parameter	32 °C	22 °C Case 4.2 :27 °C	28 °C Case 4.1 :25 °C	26 °C
Case 1.1	Adaptation	10 min	---	10 min	30 min
Case 1.2		10 min	---	30 min	30 min
Case 1.3		10 min	---	1 min	30 min
Case 2.1	Cold shock	10 min	10 min	---	30 min
Case 2.2		10 min	30 min	---	30 min
Case 2.3		10 min	1 min	---	30 min

estimated to be 0.7.

3.3 Results

The comparison between Case 1.2 (adaptation group, 30 minutes stay at the Piazza) and Case 2.2 (cold shock group, 30 minutes stay at the Main Entrance) and the comparison between Case 1.2 and Case 2.3 (cold shock group, 1 minute stay at the Piazza) are showed in this paper.

In the comparison of these cases, the differences between adaptation and cold shock were evaluated.

Case 1.1 (adaptation group, 10 minutes stay at the Piazza) indicated a similar tendency to Case 1.2. And Case 2.1 (cold shock group, 10 minutes stay at the Main Entrance) indicated a similar tendency to Case 2.2. Therefore, in this paper, 30 minutes and 1 minute stimulation cases are presented.

1) Comparison between Case 1.2 (adaptation group, 30 minutes stay) and Case 2.2 (cold shock group, 30 minutes)

The results of thermal comfort in Case 1.2, 2.2 and 2.3 are shown in Figure 3.

In Case 1.2 (adaptation), thermal sensation was cool (changed to -0.8 from -0.5) in the Grand Hall (Figure 4 (1)). On the other hand, in Case 2.2 (cold shock), it approached warmth (changed to 1.0 from 0.0) (Figure 3 (2)). Subjects felt different thermal sensation in the same thermal condition between 2 cases.

In Case 1.2, just after the subject entered the Grand Hall, comfort sensation approached to comfort from neutral (changed to 2.2 from 0.8) and even when time passed, this inclination still continued (Figure 3 (1)). On the other hand, in Case 2.2, there was not so much difference (changed to 0.0 from 0.3), even though he felt cold for a long time before he entered the Grand Hall (Figure 3 (2)). It is assumed that the warm feeling while staying in the Grand Hall decreased the sensation of comfort.

In comparison of Case 1.2 and 2.2, TOI value of Case 2.2 was higher than that of Case 1.2. TOI value indicates the oxygen saturation of the hemoglobin. In Case 2.2, the subject was forced to be in a cold situation, and he felt the cold sensation, therefore it was assumed that the oxygen saturation of the hemoglobin rose to maintain the body temperature. Because of the high TOI value and high physiological activity, the subject felt warm after he entered the Grand Hall, then it was assumed that his comfort sensation was decreased. 30 minutes cold shock may be considered to be excessive stimulation.

2) Comparison between Case 1.2 (adaptation group, 30 minutes stay) and Case 2.3 (cold shock group, 1 minute)

In Case 2.3 (cold shock, 1 minute), thermal sensation approached neutral closer than that of Case 2.2 (Figure 3 (2), (3)). However, it was also warmer than that of Case 2.1 (Figure 3 (1), (3)). Furthermore, the trend of thermal sensation of Case 3.2 after subjects entered the Grand Hall was similar to that of Case 2.2.

In Case 2.3, comfort sensation did not approach to comfort (changed to 0.3 from 1.0).

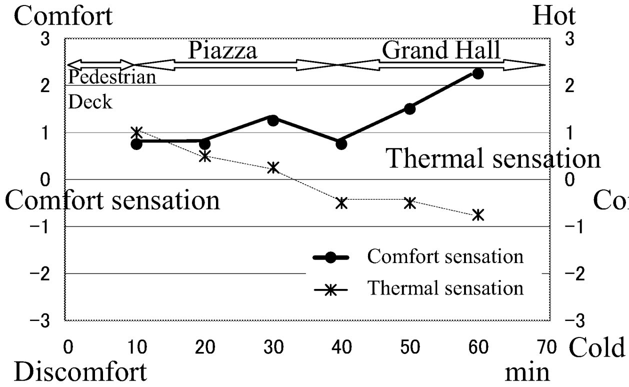
In comparison with Case 1.2 and 2.3, TOI value of Case 2.3 was also higher than that of Case 1.2.

In this experiment, high TOI value and high physiological activity occurred with the stimulation of only 1 minute cold shock.

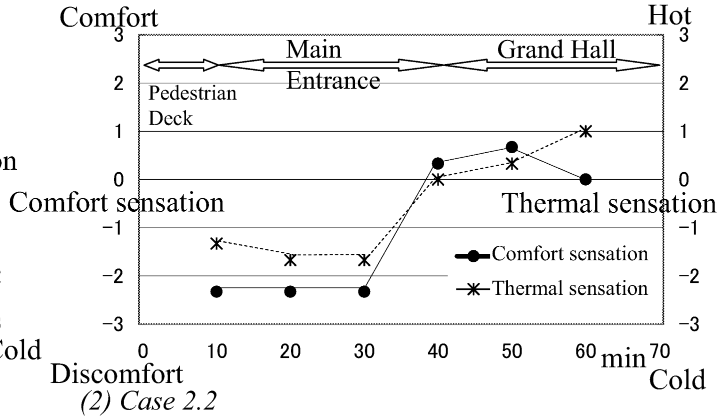
3.4 Conclusion of the building study

The influence of adaptation and cold shock on the way to the hall from outside was evaluated in the experiment. In this case, adaptation was more effective in the thermal comfort improvement than cold shock. However, there is a possibility that the effect changes depending on the amount and the time of stimulation. Therefore, it is thought that further quantification is necessary.

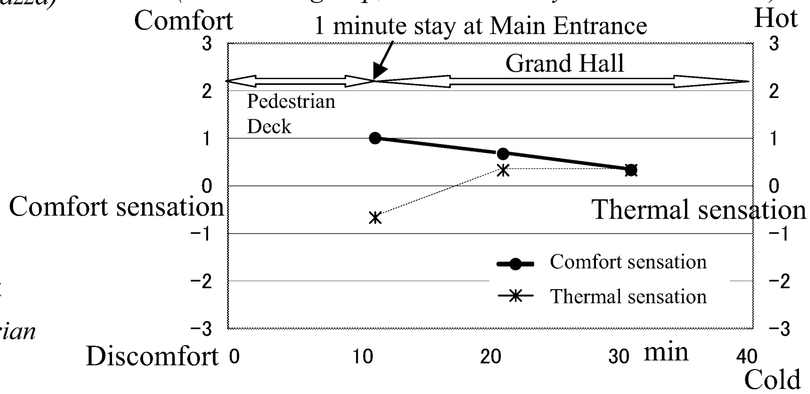
The Piazza in the performing arts center was designed with much sunshine from the light



(1) Case 1.2
(adaptation group, 30 minutes stay at Piazza)



(2) Case 2.2
(cold shock group, 30 minutes stay at Main Entrance)



(3) Case 2.3 (cold shock group, 1 minute stay at Main Entrance)

Figure 3. Results of thermal comfort

(Starting time of 10 minutes walk on Pedestrian deck was set as 0 minute in Figure 4)

ceiling. Therefore indoor climate in the Piazza seems to be located between uncontrolled outdoor climate and controlled indoor climate. By the experiment conducted in this study, the Piazza contributed to the thermal comfort of the visitors coming to the Grand Hall. Raising the preset temperature of the air-conditioning system in the Piazza would also lead to energy saving. In the Piazza, the preset temperature is 28 ^{o}C in summer, which is 2 degrees higher than in normal systems, and the measured temperature was almost 28 ^{o}C during summer. However, there were no complaints about thermal comfort from the visitors. In the Piazza, transmission heat has been reduced by at least 43 GJ/year in the cooling season.

4 CONCLUSIONS

This paper showed the experimental evaluation of thermal comfort of people moving from outdoors to indoors in summer. It also showed a building example which makes positive use of environmental change to improve thermal comfort in destination, and its evaluation by field experiments in summer.

Results of these experiments showed that actual thermal comfort was different from the stationary standard, and that it is important to know the history which the person experiences. It is necessary for appropriate HVAC control and thermal comfort to understand the influence of thermal change on human perception both physiologically and psychologically.

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