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Difference in thermal sensation and behavioral pattern of occupants between passive and active cooling strategies

ITARU TAKAHASHI*, MASAYA SAITO*, HIROYUKI MATSUOKA**, YOUSUKE ARIKAWA***, HIROAKI SUGIOKA**** AND MASANORI SHUKUYA*

*Laboratory of Building Environment, Musashi Institute of Technology
1-28-1 Tamazutsumi Setagaya-ku Tokyo, Japan, 158-0087
itaru@shu.arc.musashi-tech.ac.jp
**Urban Development Co. 1-14-6 Kudankita Chiyoda-ku Tokyo, Japan, 102-8201
***Takasago Thermal Engineering Co. Ltd. 4-2-8 Surugadai Chiyoda-ku Tokyo, Japan, 101-8321
****DAI-DAN Co. Ltd. 1-9-25 Edobori Nishi-ku Osaka, Japan, 550-8520

Abstract

We made a series of subjective experiment to grasp individual behaviors and thermal sensation of the occupants in as actual environmental condition as possible by observation using video cameras. The use of video cameras allows us to have the time-series of scenes of the occupants participating in the experiment; it also allows us to avoid disturbing their natural behaviors and sensations. In this subjective experiment, we focused on investigating how the use of cross ventilation, the use of small fans, the use of air conditioners, and the choice of a path approaching to the building influence individual behaviors and thermal sensation. It was found that most of the subjects in a room with cross ventilation were very sensitive to the fluctuation of the air current in the given thermal environment and also very active in having coolness. It does not necessarily require lower room temperature in a case that the subjects approach the room by walking in milder outdoor environment. We also made an interview on the subjects' lifestyles including the use of air conditioner and cross ventilation in their daily life. It was found that the subjects who usually use air conditioners in their daily life imagine their comfortable temperature in summer lower than the actual environmental temperature (SET*) to which they are exposed and feel comfortable.

INTRODUCTION

It is vitally important for sustainable architecture that the occupants participate actively in controlling their built environment such as opening windows and adjusting clothes by their preference in addition to designing building envelopes with various pieces of passive technology. If we have a chance to research on the thermal sensation or comfort of the occupants in actual built environment, the research should be something unlikely to disturb the natural behavioural pattern and actual sensation. This is because what should be revealed from the research is actual thermal comfort in the built environment being appreciated by the residents themselves, not by architects and mechanical engineers who do not reside there[1].

The influences of passive and active cooling strategies on the thermal sensations of the occupants have been researched by many researchers[2] [3] [4][5][6]. However there is no attempt to observe both the time-series of variation in thermal sensations and corresponding variation in individual behaviors. If such an attempt could be made, it should be designed unlikely to disturb the natural behaviors of the occupants and hardly to distort their actual sensations.

From such a view point, we made a series of subjective experiment to grasp how the natural behaviors and actual sensation of the occupants vary by observing with video cameras in a summer season[7]. The observation using video cameras allows us to have the time-series of scenes of the occupants participating in the experiment; it also allows us to avoid disturbing their natural behaviors and sensations. In this subjective experiment, we focused on investigating how the use of cross ventilation, the use of small fans, the use of air conditioners and the choice of a path approaching to the building influence individual behaviors and thermal sensation. The votes and the behaviors of the subjects were recorded by video cameras.

We also made an interview on the subjects' lifestyles including the use of air conditioners and cross ventilation in their daily life in order to know whether their lifestyle affects the thermal sensation. This is because thermal sensation or comfort against a given built environment is determined not only by physical quantities of the environment such as temperature then exposed, but also by the history of the exposure to the environment through their daily life[8].

SUBJECTIVE EXPERIMENT

The experiment was made from the 18th to 20th of August in 1998 in the campus of the faculty of information and environmental studies of Musashi Institute of Technology in Yokohama. Buildings in this campus were designed and completed in 1997 so that various passive strategies such as thermal insulation of walls and windows, cross ventilation, solar collectors, roof spraying with rainwater and others are applied.

Figure 1. shows a plan view of the fourth floor of a building in the campus used for the experiment. The outside walls and windows of this building are thermally-well insulated. We used room S and room Y for the experiment. The two rooms are located at the south side of the fourth floor. All windows of the corridor can be manually opened. Each room has a window facing south or north, and a small window above the door to the corridor. The opening area of the window facing outside is 0.75m X 1.25m and the total opening area of the small window and the door is 0.8m X 2.5m. There is an overhang above the window whose depth is 0.8m. There are two air conditioners with water-to-air heat exchangers in the attic space above the ceiling of each room.

Figure 2. is a closer look at one of the rooms. It shows the positions of sensors, video cameras, subjects and observers. We measured room air temperature, surface temperature of walls, ceilings and floors, and room air humidity at one-minute intervals. Room air velocity was measured at one-second intervals. We also measured outside wind direction and velocity, outside air temperature, outside air humidity and solar radiation at one-minute intervals on the roof of the building.

We compared the thermal sensation and behaviors in the naturally ventilated room (room S) and the air-conditioned room (room Y). The experiment was done twice a day: one is from 12:00 to 13:30 and the other is from 13:30 to 15:00. Ten subjects participated in each period of the experiment. They were divided into two groups and each group entered each room after walking through sunny hot outdoor environment for 30 minutes. They stayed in the rooms for one hour. The metabolic rate under walking outside was estimated about 2 met. The outdoor environment is formed by concrete building envelopes, pavements made of asphalt, and the sky. There is no shade against solar radiation in the outdoor path, so that the outdoor radiant environment could be severe.

All subjects were undergraduate students of Musashi Institute of Technology, and the total number who participated in the experiment was sixty; among them fourteen were female. Twelve out of sixty subjects participated in the experiment for two days and the rest for one day. We asked the subjects to wear short sleeve shirts and long pants. The clothing insulation was estimated about 0.6 clo.

We gave each subject six small placards each of which shows "hot", "suzusii", "cold", "sweating", "muggy", or "uncomfortable". The word,"suzusii" is a Japanese and it expresses for example a pleasant sensation to be felt especially when comfortable breeze is given even if the air is rather humid or a pleasant sensation to be felt as being fresh due mainly to rather low radiant temperature[9] [10]. This is not exactly equivalent to "cool" in English, and not the same as "cool" given in the seven-point scale of thermal sensation. If we must express "suzusii" in English, it turns out to be "comfortably cool".

Whenever the subject feels some sensation which is similar to the sensation written in the placards, he /she is asked to put the most appropriate placard on as shown in Photo 1. When a subject feels a sensation which is different from those six sensations, we also asked them to say whatever they feel to the microphones attached to the video cameras and not to put any placards on. The subjects were allowed to do anything except eating food and standing up. The votes and the behaviors of the subjects were recorded

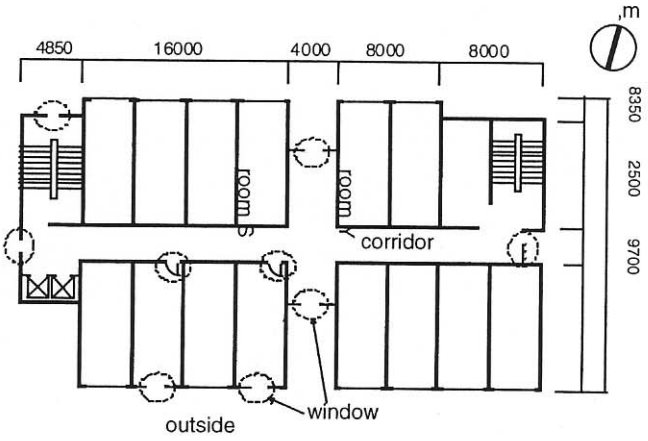

Figure 1. Plan view of the fourth floor of the building used. The two rooms (shaded) were used for the experiment. All windows are opened when the room is naturally ventilated.

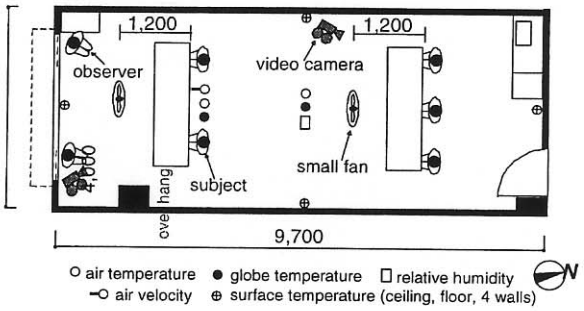

Figure 2. Plan view of one of the rooms for the experiment.

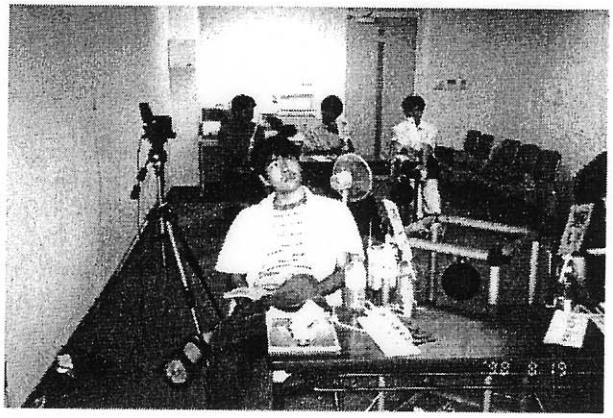

Photo 1. A scene of the subjective experiment in one of the rooms. The subjects put small placards with the words of thermal sensation on whenever they feel some thermal sensation. The subjects can do anything except eat food and stand up. Their thermal sensation and behaviours are recorded by video camera during the experiment.

by video cameras during both periods of walking outdoors and staying indoors. Two observers in each room talked to the subjects to let them relax and wrote what they found in terms of the subjects' behavior on their notes.

All luminaires in the rooms were turned off. When a room was naturally ventilated, all windows of the room and

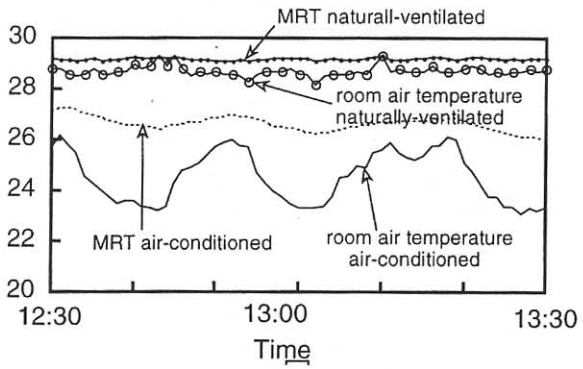

Figure 3. The variations of room air temperature and the MRT in the naturally ventilated and air-conditioned rooms.

the corridor were kept opened. When a room was mechanically air-conditioned, the set-point temperature was kept at 25°C, though the air temperature realised fluctuated according to the characteristics of the thermostat.

RESULTS OF THE EXPERIMENT

Influence of natural ventilation and air conditioning on thermal sensation and behaviors

Figure 3. shows the variations of the room air temperature and the mean radiant temperature (MRT) measured in the naturally-ventilated room (room S) and the air-conditioned room (room Y) during 12:30~13:30 on the 18th of August. The room air temperature of the naturally-ventilated room varies from 28°C to 29.5°C, and the MRT of that room remained unchanged at about 29°C. On the other hand, the room air temperature of the air-conditoned room varies quite sharply from 23°C to 26°C. The MRT of the air-conditioned room fluctuates between 26°C and 27.5°C. The mean relative humidity of the naturally-ventilated room is 65% and that of the air-conditioned room is 58%.

Figure 4. shows the variation of the air velocity of the two rooms measured on the 19th of August for reference; since the air velocity could not be recorded due to some trouble in data acquisition system on the 18th of August. The upper figure shows the air velocity of the naturally-ventilated room and the lower figure that of the air-conditioned room. The air velocity measured in the naturally-ventilated room varies from 0.1 to 2.5 m/s, and that in the air-conditioned room from 0.2 to 1.5 m/s. The air velocity in the naturally-ventilated room fluctuated more sharply than the air-conditioned room ten minutes after the occupants entering the room. This is due to the use of a small fan. The length of the interval from the minimum to the maximum air velocity in the naturally-ventilated room was 9.5 sec. The velocity of the wind coming into the room was below 0.5 m/s.

Figure 5. shows the variations of thermal sensation votes observed in the naturally-ventilated room with small fans (upper) and in the air-conditioned room (lower). Each symbol denotes one subject. The voting patterns of the five subjects in each room can be sorted out into three groups, so that we show the votes of three subjects only. We did not compute the mean values of the thermal sensation votes, but carefully investigated on the difference in individual sensation and behavioral patterns. In the naturally-ventilated room, two of the three subjects started to put "suzusii" on from other sensations such as "uncomfortable",

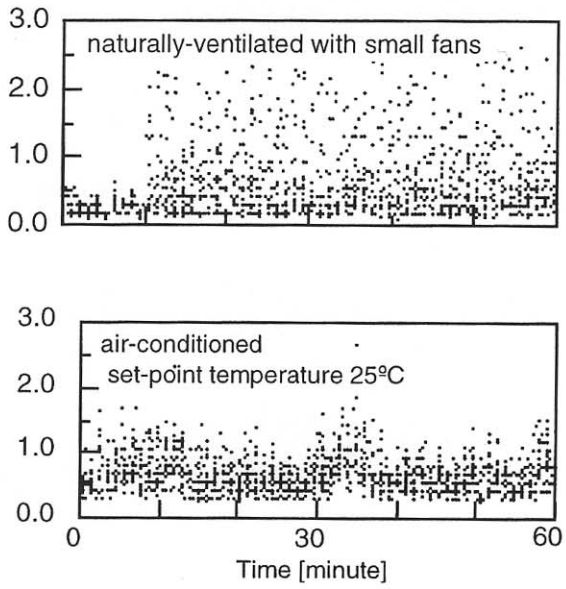

Figure 4. The variations of room air velocity measured in the naturally ventilated and air-conditioned rooms.

"muggy", "sweating" or "hot" at 12:40 when small fans started to run. They were very sensitive to the fluctuation of the air current in the given environment. The subject denoted by a symbol, 'white diamond' also started to put "muggy" on in addition to "suzusii" after 12:40. The subject 'black diamond' feels "sweating" and, or "suzusii" from the beginning, but after 12:40 his vote became "suzusii" only. No subjects vote "uncomfortable" after 12:50.

In the air-conditioned room, all subjects put "suzusii" on continuously during the experiment. Only one subject 'white circle' put "sweating" and "muggy" on at the beginning, but his votes changed to "suzusii" at 12:40 and it continued until 13:30. He finally put "cold" on in addition to "suzusii" at around 13:22.

The characteristics of thermal sensation of the subjects in the air-conditioned room are steady and uniform, while

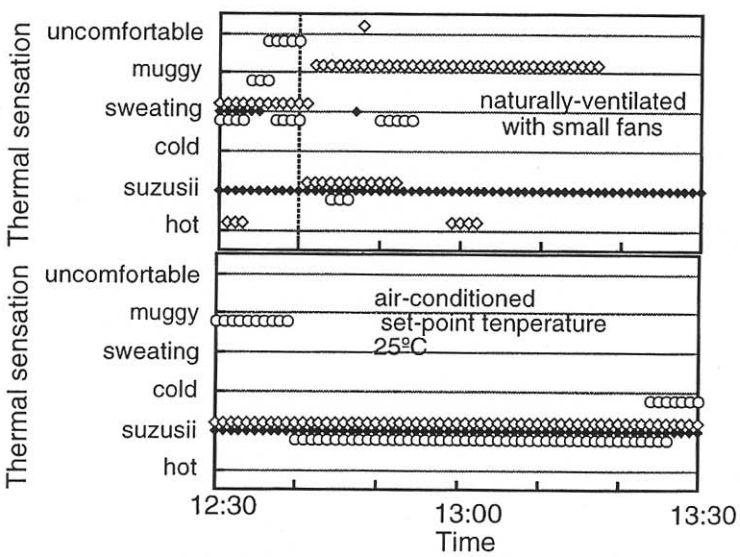

Figure 5. The variations the thermal sensation which are voted in the naturally ventilated and in the air-conditioned rooms.

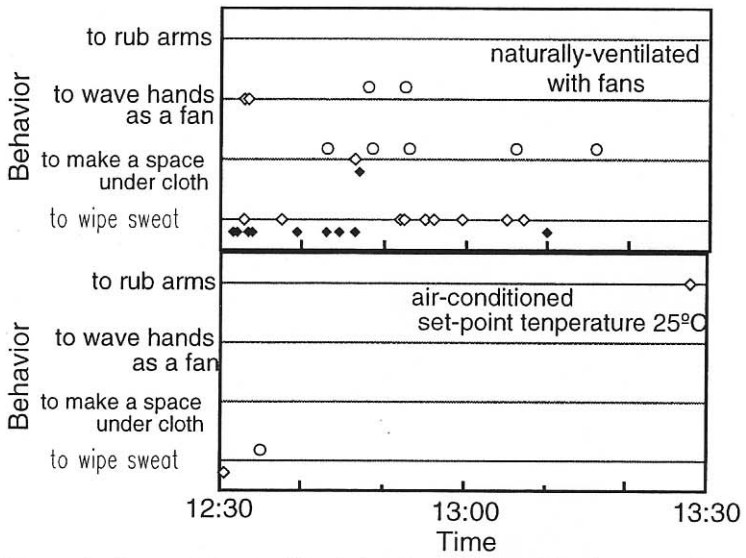

Figure 6. The variations of the behaviors observed in the naturally-ventilated and in the air-conditioned rooms.

those of the subjects in the naturally ventilated room are unsteady and diverse. The sensation "suzusii" voted in the air-conditioned room is due to low radiant and air temperature; on the other hand the sensation "suzusii" voted in the naturally ventilated room is due to comfortable breeze.

Figure 6. shows the variations of behaviors observed through video cameras in the naturally-ventilated room and in the air-conditioned room. In the naturally ventilated room, from the beginning to the end of the experiment, the behaviors such as "to wave hands as a fan", "to make a space under cloth with hand" and "to wipe sweat by hand" are frequently observed. On the other hand, there is little behaviors observed in the air-conditioned room. There is a clear contrast in the variation of behaviors between the naturally-ventilated room and the air-conditioned room. The subjects in the naturally-ventilated room were very *active* in having coolness or comfort, while the subjects in the air-conditioned room do almost nothing themselves. The use of air conditioners made the sensation of occupants uniform, and might have made their behavior *passive*.

Influence of the outdoor thermal environment approaching to the building on thermal sensation and behaviors

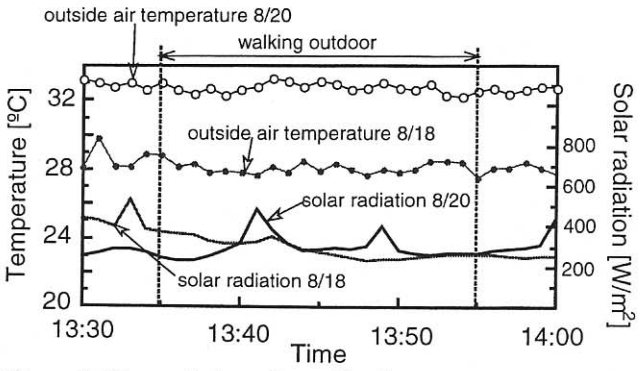

Figure 7. The variation of outside air temperature and solar radiation measured on the 18th and the 20th of August.

Figure 7. shows the variation of solar radiation and outside air temperature measured on the 18th and the 20th of August. The mean outside air temperature of the 18th is 28.5°C and that of the 20th is 33°C. The solar radiation on the 20th is a little larger than that on the 18th. Namely the outside thermal environment of the 20th was hotter than that of the 18th. Figure 8. shows the variations of the room air temperature and the MRT measured in the air-conditioned room during the 13:00~14:00 period on the 18th and the 20th. The room air temperature varies between 23°C and 26°C, and swings twice on the both days. The MRT experienced on both days remained almost constant at about 26°C. The room air velocity of both days was almost similar to that of the 19th shown in Figure 4. The mean relative humidity of the 18th is 62% and that of the 20th is 64%. Therefore, there is little difference in the indoor thermal environment between the 18th and the 20th.

Figure 9. shows the variation of the thermal sensation of the 18th and the 20th. The upper figure shows the results of the 18th and the lower is the 20th. In the experiment of the 18th, the vote "cold" occurs twice when the air temperature goes down to the lowest, on the other hand in the experiment of the 20th, the vote "cold" occurs only once, when the room air temperature goes down to the lowest at the second time (after 14:30). This difference in the votes of "cold" is caused by the difference in the outdoor thermal environment, since there is little difference in the indoor thermal environment between two days. In the experiment of the 20th the subjects were exposed to hotter outdoor thermal environment and as a result they did not sense the first decrease of the room air temperature. It may be possible from this that the occupants can feel comfortable in the air-conditioned room whose set-point temperature is higher, if they enter a building from milder outdoor environment. It is very important to design the outdoor and indoor thermal environment as a whole. The outdoor environment where many trees shade solar radiation and the secretion and evaporation by leaves mitigate the hotness could work as a pre-cooling environment before entering the air-conditioned built environment.

LIFESTYLE AND CONSCIOUSNESS OF THE SUBJECTS

From the results of the subjective experiment, we could grasp how the passive and active cooling means influence individual thermal sensation and behaviors. However, the thermal sensation and comfort of the occupants are not necessarily determined by the physical effects of cooling means only, but also their lifestyles and consciousness to cooling means. Therefore we interviewed twenty out of sixty subjects participated in the summer experiment in December 1998. We asked them about "Which cooling means do you chose first, when you feel hot?", "Which temperature do you regard as comfortable in summer?" and others.

We compared the temperature that the subjects regard as comfortable in summer and the SET* in which the subjects actually felt "suzusii" in the summer experiment. The SET* was calculated from the data of the indoor thermal environment in which the subject felt "suzusii", assuming that the metabolic rate is 63.8 W/m^2 and clothing insulation is 0.6 clo.

Figure 10. shows the relationship between the comfortable temperature imagined by the six subjects who usually use air conditioners and the SET* in which they felt actually "suzusii" in the summer experiment. The comfortable temperature imagined by subject A, B, C, D and F range from 18°C to 20°C, and that by subject E is 26°C. On the other hand, the SET*s in which the subjects actually felt "suzusii" range from 22°C to 24°C, and all of them are within the comfort zone. The comfortable temperature imagined by the subjects except subject E are lower than the SET* in which they actually felt "suzusii", and also lower than the recommended comfort zone of SET*. This may be due to misunderstanding of their comfortable temperature by these subjects. If they set the thermostat according to what they believe comfortable, it could result in the waste of electricity for air conditioning and moreover bring about a health problem. It could be necessary for them to recognise which temperature is actually comfortable by environmental education.

Only subject E imagined his comforatble temperature

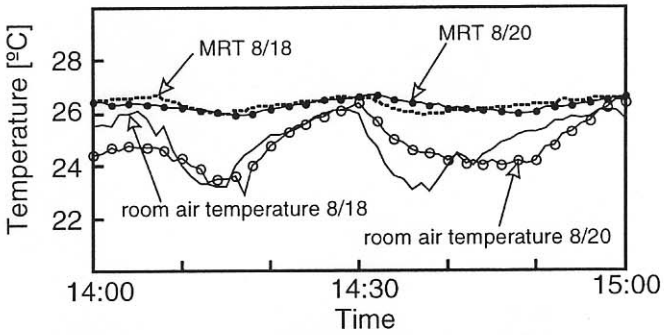

Figure 8. The variations of air temperature and MRT in the air-conditioned room measured on the 18th and the 20th of August.

higher than the actual SET*. As matter of fact, subject E was one of the under-graduate students who belonged to our laboratory. His experience in learning building science for several months did not change his lifestyle such as using air conditioners very often, but it certainly changed his consciousness of the comfortable temperature. We confirmed that he told us later that he would have answered lower temperature, if he did not learn building science in our laboratory.

Figure 11. shows the relationship between the comfortable temperature imagined by the subjects who do not use air conditioners in summer and the SET* in which they actually felt "suzusii" in the experiment. The comfortable temperature imagined by subject G, I, J, K ranges from 22.5°C to 28°C, and that by subject H is 18°C. Except subject H, these are roughly within the comfort zone of SET*. The SET*s in which the subjects actually felt "suzusii" range from 22°C to 23°C, and these are also within the comfort zone. The comfortable temperature imaged by the subjects who do not use air conditioners are higher than SET* in which the subjects felt "suzusii". This result is totally opposite to the results shown in Figure 10. The difference between the comfortable temperature imagined by the subjects who do not use air conditioner in summer

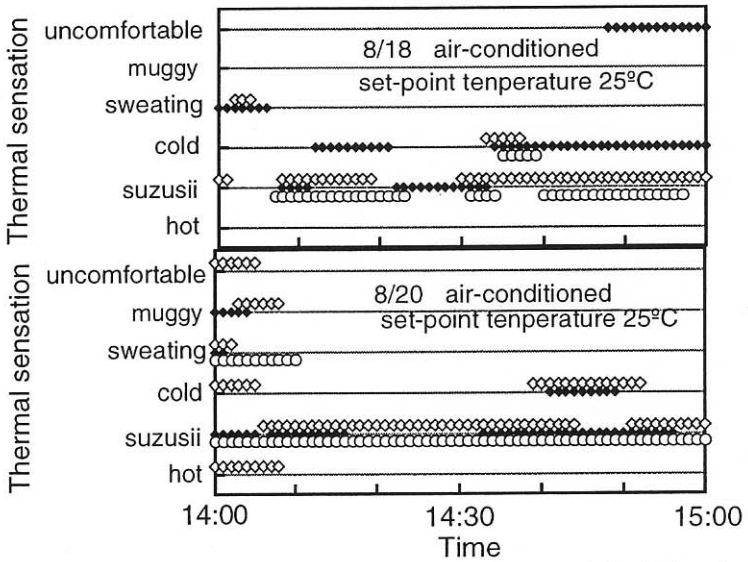

Figure 9. The variations of the thermal sensation voted for in the air-conditioned room on the 18th and the 20th of August.

and the SET* in which the subjects actually felt "suzusii" in the experiment would not cause a serious problem.

CONCLUSION

We made a subjective experiment to grasp how the use of cross ventilation, the use of air conditioners, the use of small fans, and the outdoor thermal environment approaching to the building in question influence the thermal sensation and the behaviors of the subjects, and a survey with interview on the lifestyle and consciousness of the subjects. What we found are as follows:

1) The observation of the subjects in the indoor and outdoor environment by video cameras enabled us to grasp the time-series of variation in the behaviors and the sensation of the subjects.
2) In the naturally ventilated room, the subjects were very sensitive to the fluctuation of the air current. There is no vote of "uncomfortable". The characteristics of the thermal sensation is unsteady and diverse. The behaviors such as "to wave hands as a fan", "to make a space under cloth with hand" and "to wipe sweat by hand" were frequently observed. The subjects were very *active* in having coolness.
3) In the air-conditioned room, the subjects continuously voted "suzusii". The characteristics of the thermal sensation is steady and uniform. We observed almost no behavior such as "to rub arms", "to wave hands as a fan","to make a space under cloth with hand" and "to wipe sweat by hand". The use of air conditioners might make the sensation of the subjects uniform, and also make their behavior *passive*.
4) When the subjects entered the air-conditioned indoor thermal environment, the subjects who approached from hotter outdoor environment did not vote "cold", while the subjects who approached from milder outdoor environment voted "cold". This result suggest us that it does not necessarily require lower temperature provided that the subjects reach a room walking from better outdoor environment.
5) The subjects who usually use air conditioners imagined their comfortable temperature lower than the SET* in which they actually felt "suzusii". The comfortable temperatures imagined by the subjects were 18°C to 20°C and they were lower than the recommended comfort zone of SET*. While the subjects who do not use air conditioners imagined the comfortable temperature higher than SET* in which they actually felt "suzusii". Both of the comfortable temperature and the SET* were within the comfort zone of SET* in the case of the subjects who do not use air conditioners. It would be necessary for the subjects who usually use air conditioners to have an adequate understanding of which comfortable temperature to keep the health of occupants and thereby to reduce the exergy consumption for cooling.

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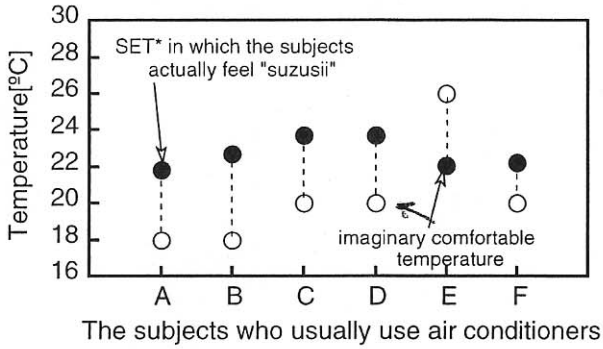

Figure 10. The relation between the comfortable temperature imagined by the subjects who usually use air conditioners in summer and SET* in which they actually felt "suzusii" in the experiment.

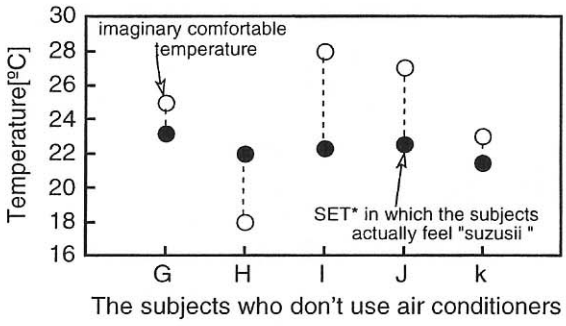

Figure 11. The relation between the comfortable temperature imagined by the subjects who do not use air conditioners in summer and SET* in which they actually felt "suzusii" in the experiment.

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