Experimental Study on Thermal Cognition Developed through Daily Experience in the Built Environment during Summer Seasons

T. Iwamatsu and M. Shukuya

Musashi Institute of Technology, Japan

E. Kataoka

Nikken Sekkei Ltd., Japan

Y. Hoshino

Tetens Consulting and Engineering Co., Ltd., Japan

ABSTRACT

This paper discusses whether there is thermal cognition acquired through daily experience in the built environment during summer seasons. For this purpose, we analysed the results of a subjective experiment to reveal the relationship between subjective responses and environmental quantities obtained from two experimental small wooden buildings: one has a radiative cooling system on the ceiling and the other has a conventional convective cooling system. The ceiling surface temperature of the building with radiative cooling was controlled at around 26℃, much higher than that of the conventional radiative cooling panels. This is because our investigation of this experiment originally aimed at clarifying the threshold level of thermal cognition provided by high-temperature radiative cooling systems.

We classified the lifestyles of 35 participated subjects into two types: one is to use mainly convective cooling and the other to use mainly natural ventilation for long hours. We also sorted out the same subjects into the other two types, whether they like air-conditioned room space or dislike it.

The percentage of comfort votes decreases as the indoor radiant temperature increases. The same was true for room air temperature. The percentage of comfort votes drops sharply beyond 30℃ in this experiment. There is a clear difference in the percentage of comfort votes between those who prefer air conditioned room spaces and those who dislike it. There is a tendency that those who dislike air conditioned space accept room spaces with higher humidity, e.g. over 60 % rh, provided that both mean radiant and air temperatures are lower than 30℃. It suggests that there exists acquired thermal cognition developed through daily experience in the built environment, which is different from person to person depending on what kind of cooling he or she has been exposed to.

1. INTRODUCTION

Convective cooling has been spread as a typical cooling measure in hot and humid regions. The saturation level of heat-pump air conditioners in Japan is over 80 percent of household in 2005. There is also radiative cooling as another cooling measure, but it is not spread as convective cooling is. Most of the radiative cooling makes the surface temperature of cooling panels well below the dew-point temperature to dehumidify the room air. As far as radiative cooling systems make the low surface temperature to dehumidify, they are not so different from convective cooling as they should be.

In our previous research (2007), we focused on the feasibility of high-temperature radiative cooling without dehumidification but with moist-air exhaustion by natural ventilation. This system aims not only at reducing fossil-fuel consumption but also at mitigating heat-island phenomena, and avoiding so-called "space-cooling syndrome" without sacrificing thermal comfort. Even if such a cooling system may contributes to reducing fossil-fuel use and mitigating heat-island phenomena, people who are so accustomed to air-conditioned room space in summer seasons may not necessarily accept the thermal environment provided by high temperature radiative cooling.

In human brain, the information given from the environment through thermo-receptors distributed all over human body is always evaluated in relation to "comfort" or "discomfort", and such relations are memorized as a comfort measure (Matsumoto et al. 1996). Even if people are exposed in the same thermal environment, their thermal cognitions are not necessarily the same because the thermal background could be different each other. This is because the thermal background must have grown up by their thermal experience which is stored in their brains from birth to present all the time. We call such thermal cognition as "acquired thermal cognition". Although the existence of thermal cognitions has been pointed out previously, e.g. Matsushita et al. 2006, why and how the individual differences emerge have not yet been clarified.

One of the experimental research projects dealing with luminous environment suggests that there must be a relationship between the brightness cognition acquired through daily experiences and individual lifestyles associated with luminous environment (Naoi et al 2003).

We investigated here the relationship between the indoor thermal condition and the thermo physical cognition acquired through daily experience of thermal environment during summer. This is to develop a rational radiative cooling measure to be accepted by as many as people as possible.

2. EXPERIMENTAL SET-UP

We used two identical small wooden buildings for experiment in a research institute which is located in Tsukuba: one has a radiative cooling panel on the ceiling (Bldg. RC); and the other a convective cooling unit (Bldg. CC). *Photo 1* shows the south-facing appearances of Bldgs. RC and CC, respectively. *Figure 1* shows the floor plan of Bldg. RC.

The shading devices are different in both buildings. Bldg. RC has an external shading device and Bldg. CC has an ordinary internal white curtain as shown in Photo 1. This is because external shading is regarded as the other radiative cooling panel to make the window surface temperature lower than that with internal shading.

The experiment was made from 15th to 26th of August, 2005. In Bldg. RC, we prepared three cases of cooling and ventilation: the first is radiative cooling without ventilation for two days (15th and 26th); the second is radiative cooling with natural ventilation (22th and 25th); and the third is no radiative cooling but natural ventilation (18th and 19th). The ceiling surface temperature was controlled at approximately 26 ℃ for all of those three cases. In Bldg. CC, on the other hand, the room air was conditioned aiming at a set-point temperature of 28 ℃.

Figure 2 shows one unit of the whole experimental schedule. Prior to the subjective experiment, we conducted questionnaire of lifestyles in summer seasons. *Table 1* shows some of the questions used to sort out subjects in terms of lifestyles. After the subjects answered the questions, we asked them to walk with us for 5 minutes before entering one of the experimental buildings.

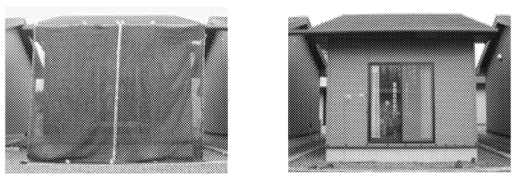

Photo 1: Two experimental buildings with radiative cooling (Bldg. RC, left) and convective cooling (Bldg. CC, right)

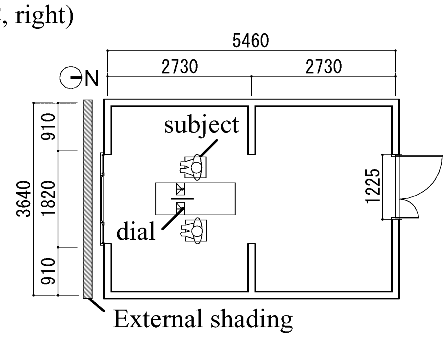

Figure 1: Floor plan of Bldg. RC

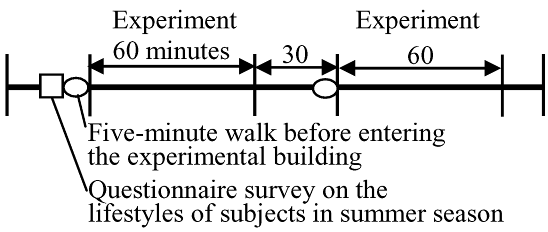

Figure 2: One unit of experimental schedule

Table 1: Questions used in questionnaire survey

a)	How long in a day are you usually exposed to air-conditioned room space at home?
b)	How long in a day do you usually keep the windows open for ventilation at home?
c)	Do you like air-conditioned space?

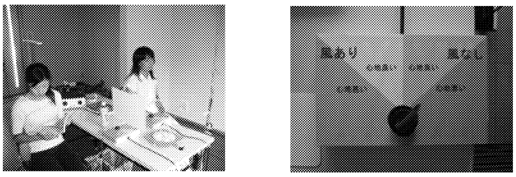

Photo 2: Two subjects at experiment and the dial used for vote. The Japanese characters on the dial box indicate the following: "風あり" for "feel air current"; "風なし" for "feel no air current" ; "心地よい" for "comfortable" ; and "心地悪い" for " not comfortable".

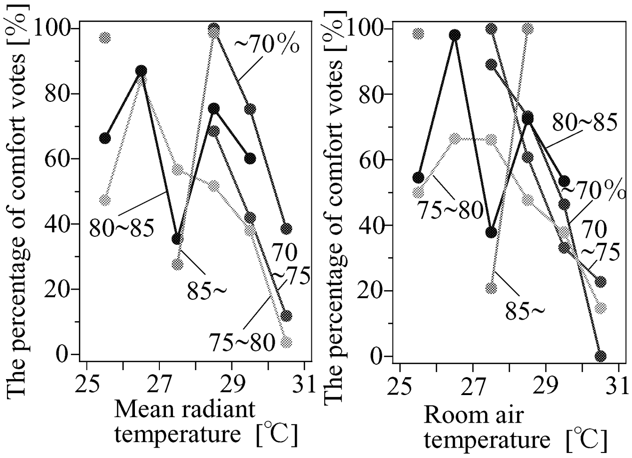

Figure 3: The relationship between the percentage of comfort votes and mean radiant temperature or air temperature at each range of 5% of relative humidity.

Photo 2 shows two subjects participating in the experiment and one of the dials for voting. Two subjects stayed in one of the buildings for one hour; that is, four subjects simultaneously in two buildings. After one hour of the experiment, the four subjects took a rest for thirty minutes and then they experienced the other building. Thirty-five subjects participated in this series of experiment. During the experiment, the subjects wore light cloths and were seated.

We asked each subject to choose one of the following four votes by the dial shown in Photo 2: "feel air current and comfortable", "feel air current but not comfortable", "feel no air current but comfortable", and "feel neither air current nor comfortable", whenever they perceived any change in either air current or comfort. These four votes were indicated by the dial, whose signal was recorded at one-second intervals.

Measured environmental quantities were wall surface temperature, air temperature, relative humidity, air-current velocity, transmitted solar irradiance and others.

3. RELATIONSHIP BETWEEN ENVIRONMENTAL QUANTITIES AND THEMAL COMFORT

We counted the number of four votes mentioned above, at each 1℃ range of mean radiant temperature and room air temperature, respectively. We merged two kinds of votes, "feel air current and comfortable" and "feel no air current but comfortable", into "comfort votes", because it was rare in this experiment that the subjects voted "feel air current and comfortable". The same was done for "not comfortable". We defined "percentage of comfort votes" as the ratio of the number of "comfort votes" to all votes belonging to each 1℃ range of temperature.

Figure 3 shows the relationship between mean radiant temperature or room air temperature and the percentage of comfort votes at each range of 5% of relative humidity. The horizontal axis of the left-hand side graph is mean radiant temperature and the right-hand side is room air temperature. The percentage of comfort votes decreases as mean radiant temperature increases and the same is true for room air temperature. The percentage of comfort votes drops sharply beyond 30℃.

Looking at the range of mean radiant temperature from 28 to 31℃, three lines of the percentage of comfort votes seem to have similar slopes but different intercept if they are extended so that they reach the vertical axis. The lower the relative humidity is, the larger the intercept. On the other hand, such tendency cannot be seen for room air temperature. It suggests that the thermal comfort must be connected with mean radiant temperature and relative humidity.

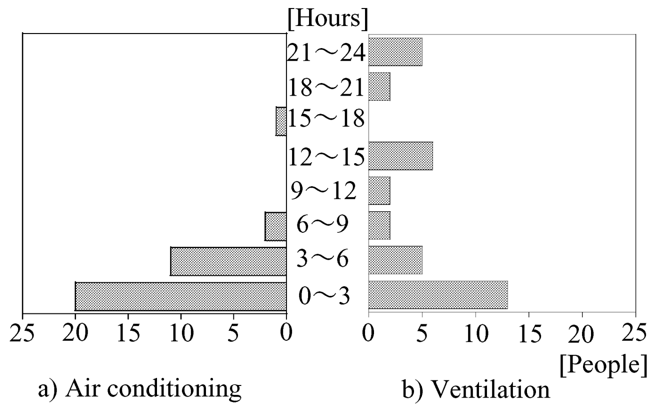

Figure 4: The results of the questionnaire survey which asked the exposure hours of air conditioning and cross ventilation for one day at the subjects' houses in summer

Figure 4 shows the results of survey which asked the exposure hours of air conditioning and cross ventilation for one day at the subjects' homes in summer.

The left-hand side graph shows the relationship between the number of the subjects and the exposure hours in terms of air conditioning and the right-hand side that in terms of cross ventilation.

Many of the subjects use air conditioners shorter than 3 hours. The air-conditioner use of over 15 hours per day is the longest in this survey. The number of the subjects who do ventilation shorter than 3 hours is the largest. The number of the subjects scatters in terms of cross ventilation than that in terms of air conditioners.

We sorted out the subjects into two types based on the results. One is a group of eleven subjects who use air conditioner longer than 3 hours and do cross ventilation shorter than 9hours and the other twelve subjects who do cross ventilation longer than 9 hours and use air conditioner shorter than 3 hours. We called the former group as "active cooling group" and the latter as "passive cooling group".

We also sorted the same subjects into the other two types, a group of the subjects who prefer to air-conditioner use and the other group of the subjects who dislike air-conditioner use. The numbers of subjects who like and dislike air conditioner are 19 and 14 persons, respectively. The total is 33, since two subjects did not answer whether they like or dislike air conditioner.

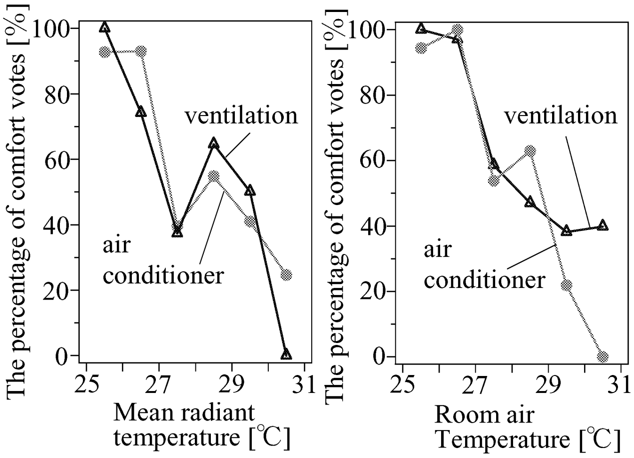

Figure 5: The relationship between the percentage of comfort votes and mean radiant temperature or air temperature. Two lines in respective graph represent two types of lifestyles: active cooling group or passive cooling group

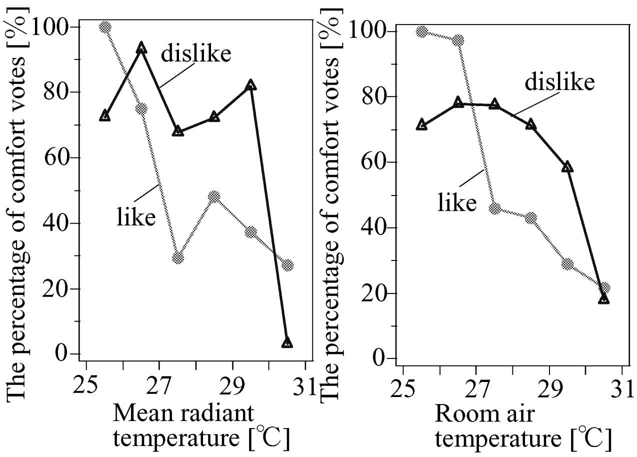

Figure 6: The relationship between the percentage of comfort votes and mean radiant temperature or air temperature. Two lines in respective graph represent the subjects who like air conditioner and those who dislike air conditioner.

Figure 5 shows the relationship between the percentage of comfort votes and temperatures. The horizontal axis of left-hand side graph is mean radiant temperature and the right-hand side room air temperature. There are two lines in respective graphs: one is for active cooling group and the other for passive cooling group. The difference in the percentage of comfort votes between two groups is not large at any values of mean radiant temperature. The same applies to room air temperature in the range from 25 to 29℃. In the range of room air temperature higher than 29 ℃, the percentage of comfort votes of "passive cooling group" is relatively larger than that of "active cooling group”. It suggests that the subjects who do cross ventilation for long hours per day seems to accept thermal environment with the air temperature of over 29 ℃.

Figure 6 shows the relationship between the percentage of comfort votes and mean radiant temperature or air temperature. One of the two lines in each graph represents the subjects who like air conditioner and the other the subjects who dislike air conditioner. The difference in percentage of comfort votes is large compared to that shown in Figure 5. The difference between “like” group and “dislike” group is remarkable more than in the case of a comparison of “active cooling group” and “passive cooling group”. In the range from 27 to 30 ℃ either for mean radiant temperature or room air temperature, the percentage of comfort votes by the subjects who dislike air conditioner is higher than those by the subjects who like air conditioner. On the other hand, for the mean radiant temperature or room air temperature lower than 26℃, the percentage of comfort votes obtained from the subjects who like air conditioners is nearly 100 %, though that obtained from subjects who dislike air conditioner is 70%. It suggests that the subjects who dislike air conditioner are not tolerant to thermal environment with lower temperature.

So far, we have focused on either mean radiant temperature or room air temperature in relation to the percentage of comfort votes, but we should also examine the influence of room air relative humidity. Therefore, we further investigate how the room air humidity affects the thermal comfort vote of the subjects.

Figure 7 shows the relationship between the percentage of comfort votes in the case of the subjects who like air conditioner and *Figure 8* in the case of subjects who dislike air conditioner. In the range of mean radian temperature or room air temperature well below 27℃ in Figure 7, the percentage of comfort votes turns out to be larger than 50%, though the relative humidity is very high over 80%, which was due to the limitation of our experimental conditions realized.

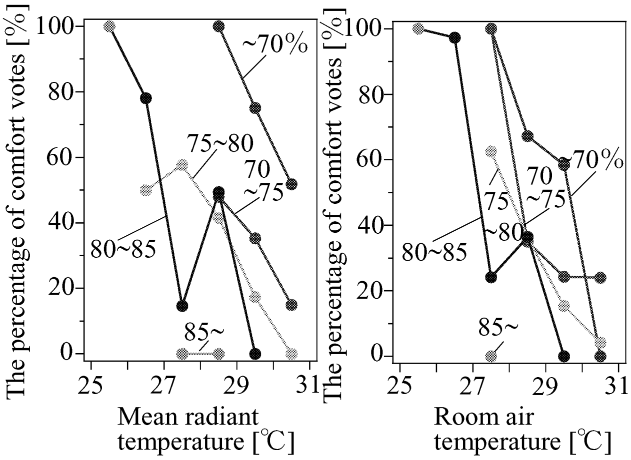

Figure 7: The percentage of comfort votes obtained from the subject who “like” air conditioner and its relations to mean radiant temperature or room air temperature with a parameter of relative humidity

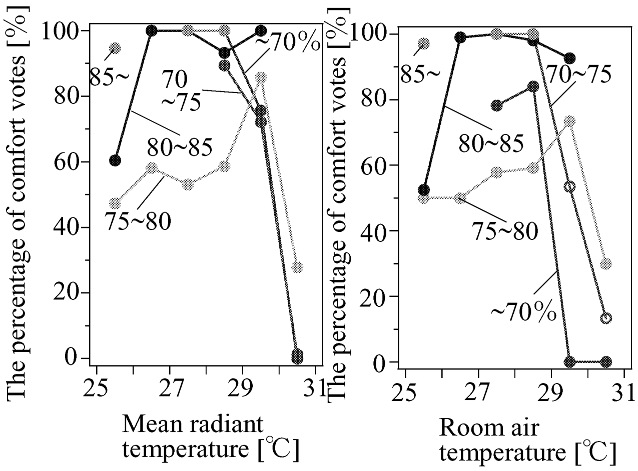

Figure 8: The percentage of comfort votes obtained from the subject who “dislike” air conditioner and its relations to mean radiant temperature or room air temperature with a parameter of relative humidity

The percentage of comfort votes of those who dislike air conditioner shown in Figure 8 appears much higher than that obtained from the subjects who like air conditioner. This is obvious under the condition of mean radiant temperature or air temperature below 29℃. They seem to be tolerant even to the relative humidity higher than 80%. This result suggests that thermal environment with over 60%rh are acceptable to those who dislike air conditioner provided that mean radiant temperature and room air temperature are lower than 30℃.

4. CONCLUSION

We conducted an experiment using two small identical wooden buildings to make clear the relationship between the thermal cognition acquired through daily experience in the built environment during summer seasons and the indoor thermal conditions, to which the subjects were exposed in this experiment. We sorted out the four types of subjects in terms of their lifestyles during summer and preference of air-conditioned room space.

The relative humidity and mean radiant temperature influence significantly on the percentage of comfort votes.

There was a clear difference in the percentage of comfort votes between the subjects who like air conditioner and those who dislike air conditioner but little difference between the subjects who use air conditioner and those who do cross ventilation much. It suggests that the preference of air conditioner and the associated thermal comfort must be grown up through their daily thermal experiences. Therefore, we have to investigate what kind of daily thermal experiences allows people to accept the thermal environmental condition provided by a different cooling measure from conventional convective cooling measure without sacrificing thermal comfort.

The percentage of comfort votes obtained from the subjects who "dislike" air conditioner is higher than that obtained from the subjects who "like" air conditioner under the condition of temperature higher than 27℃. The subjects who dislike air-conditioned room space are tolerant to the thermal environment of high relative humidity over 60% if the mean radiant temperature or room air temperature are below 30℃. On the other hand, the subjects who like air-conditioned space are not tolerant to the thermal environment with high humidity unless the temperature is quite low. In summary, we regard that there exists thermal cognition as there is the acquired brightness cognition.

People who like air-conditioned space might not be able to accept immediately the high-temperature radiative cooling combined with natural ventilation, because they are not accustomed to such a thermal environmental condition with relatively high temperature and high humidity. During the course of their exposure themselves to air-conditioned room space for long hours and for many times during summer, their brains must have made a lot of positive evaluation of low temperature and low humidity. It is also very likely that their sweat glands may become inactive and the perspiration may not function properly due to the fact that they have been exposed to air-conditioned room space for a long time. This is possibly the main reason why those subjects who like air conditioner did not accept relatively high temperature and humidity.

It is important to develop thermal cognition that can accept the relatively high temperature and humidity by thermal environmental adjustment with passive strategies such as solar control and natural ventilation, because such thermal cognition would accelerate the development of new types of radiative cooling measure.

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REFERENCES

Iwamatsu, T., Hoshino, Y., Kataoka, E. and Shukuya, M. (2007), Exergetic Evaluation of High-Temperature Radiative Cooling Combined with Natural Ventilation, *Proceedings of Building Low Energy Cooling and Advanced Ventilation Technologies in the 21st century 2nd PALENC Conference Volume 1*, pp.441-445.

Matsumoto,G. et al. (1996), Brain, Mind and Computer, *Maruzen*, pp.207-233.(in Japanese)

Matsushita, H., Horie, Y., Izumi, T and Aoki, K. (2006), An Observational Study on the Individual Thermal Sensation and Its Relationship with Environment, *Journal of Biometeorology, No. 43,*pp. 67-77. (in Japanese with English abstract)

Naoi, T., Wakatsuki, T., Takeuchi, A. and Shukuya, M (2003), An Experimental Study on Brightness Sensation Acquired Through Experiences, *Journal of Environmental Engineering (Transaction of AIJ), No.569,* pp.55-60. (in Japanese with English abstract)