Comparison of Physical and Psychological Aspects of Light and Heat Radiation Brought by Daylighting

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ABSTRACT

This paper describes the merit of daylighting by comparing the physical and psychological aspects of light and heat radiation. We prepared three rooms: direct lighting with fluorescent lamps; indirect lighting with incandescent lamps; and daylighting alone. We conducted physical measure-ment associated with light and heat, together with subjective experiments in terms of luminous and thermal sensations.

The measurement was done in August, 2006, and also in December, 2007. In summer, the air temperature of the room with daylighting alone was lower than two other rooms with electric lighting. On the other hand, in winter, the air temperature of the room with daylight-ing alone was higher than two other rooms. There was no vote indicating either too bright or too dark in the case of daylighting. Most subjects did not feel heat radiation from lighting except daylight in winter. More than 50% of the subjects prefer daylighting to electric lighting.

This confirms that daylighting should be retreated as one of the passive strategies because it creates the moderate brightness while at the same time contributes to creating moderate coolness in summer and moderate warmth in winter.

1. INTRODUCTION

Electric lighting is now used in most building space through day and night and thereby the role of daylighting seems almost forgotten. Therefore, daylighting has a large potential in reducing the use of fossil fuel. Whether it is electric light or daylight, the heat is generated by lighting so that it is important to consider the change, namely, from light to heat. It is necessary not only to quantify the physical behavior of the light sources, but also to reveal the occupants' sensations to light and heat radiation.

There have been little studies which concerned about light and heat radiation from lighting and their associated comfort. It is extremely important to make thermal environment comfortable, while at the same time making luminous environment comfortable. We investigated the physical aspects of luminous and thermal environments by setting three patterns of lighting, and also made the subjective experiment with respect to the luminous and thermal sensations in these rooms, where we assumed the subjects read books or take notes.

2. EXPERIMENTAL SET-UP

We used three classrooms on the third floor of a building of Yokohama campus, Musashi Institute of Technology. The measurement was done in August, 2006 and also in December, 2007. Summer measurement was done from 13:30 to 18:30 of 24th and 25th of August followed by subjective experiment from 28th to 30th. Winter measurement was done from 9:00 to 16:30 of 21st and 22nd of December and the subjective experiment on 21st.

Table 1 shows three illumination types that we examined. We prepared daylighting alone, indirect lighting with incandescent lamps, and direct lighting with fluorescent lamps.

Table 1: Tree illumination types

type	source	illuminance [lx]*
Daylighting alone	windowpane with overhang	60~780 (summer) 90~1500 (winter)
Indirect lighting with incandescent lamps	incandescent lamps of 60W each, 6 pieces	40
Direct lighting with fluorescent lamps	fluorescent lamps of 32W each, 12 pieces	1100

* the illuminance was measured at the desk-top surface.

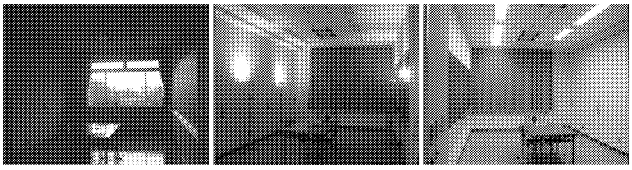
Photo 1 shows the three experimental rooms. *Figure 1* shows the room plan, the light sources, and the instrument for measurements.

In the room for direct lighting with fluorescent lamps and in the room for indirect lighting with incandescent lamps, their windows were blocked with thermally-insulating boards of 50mm thick to prevent light and heat that may enter the rooms from the windows unless there are those. We put the curtains as shown in Photo 1. In the room with daylighting alone, the curtain was opened fully, but the direct solar radiation did not transmit into the room space in summer case, because there is overhang. The windows and the door were closed and we did not use air conditioners in all three rooms. We measured outdoor and indoor air temperature, solar radiation, the indoor illuminance, air-current velocity, the wall surface temperature and light-source surface temperature.

We performed the subjective experiment with these rooms. The number of subjects was sixteen in summer experiment and eight in winter. We asked the luminous and thermal sensations and the associated preference of the subjects shown in *Table 2*. The acceptable level of desk-top illuminance was asked only at the summer experiment.

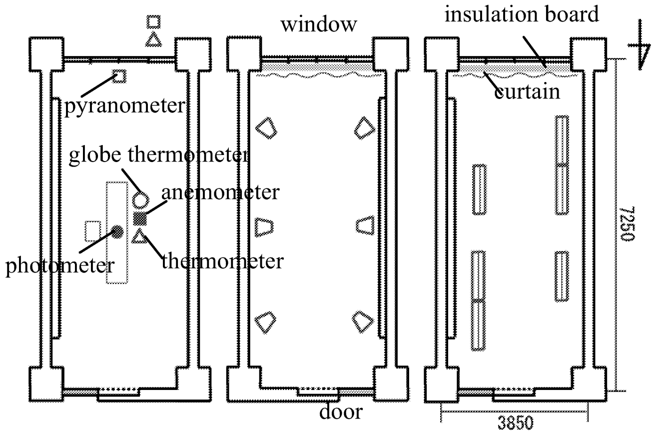
Figure 2 shows the timeline of the subjective experiment in each of three rooms. In the subjective experiment in summer, the subjects experienced each of the three rooms for 50 minutes, and in winter, they experienced each for 10 minutes. All of the subjects went through the timeline shown in Figure 2 three times within one day.

In the summer experiment, the subjects first stay with the maximum-illuminance condition.



Daylighting alone | Indirect lighting with incandescent lamps | Direct lighting with fluorescent lamps

Photo 1: Three experimental rooms



Daylighting alone | Indirect lighting with incandescent lamps | Direct lighting with fluorescent lamps

Figure 1: The plan view and the settings of light sources and measuring instruments

Table 2: The contents of questionnaire

- luminous sensation
  bright too much / bright much / bright enough / dark a little / too dark
- thermal sensation
  very hot / hot / neither hot nor cold / cold / very cold
- sensation to heat radiation
  feel much heat / feel heat a little / feel no heat
- acceptable lowest desk-top illuminance
- preference of task-ambient lighting or ambient lighting alone
- preference of the three types of illumination

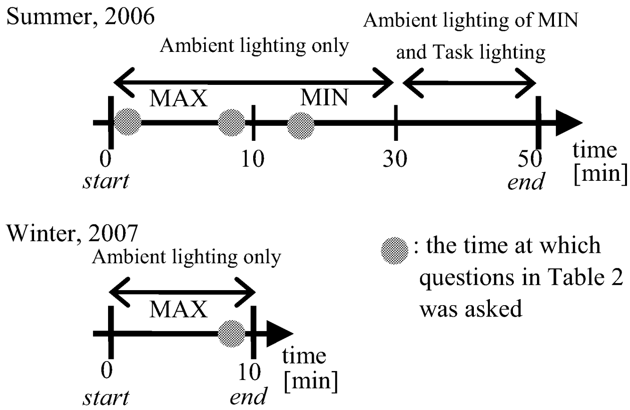


Figure 2: The timeline of the subjective experiment in one room

We call this condition MAX. Then, we decreased the illuminance by the dimmers for electric lighting and the curtains to make the minimum-illuminance condition for daylighting. We call this condition MIN. After this minimum-illuminance condition (MIN), the subjects experienced the task lighting with ambient lighting of MIN. In the winter experiment, the subjects experienced ambient lighting only. During these experiments, the subjects read books or took notes.

3. EXPERIMENTAL RESULTS

Figure 3 shows the air temperature, the solar irradiances and cumulative energy input from the light sources. In two rooms with electric lighting, the cumulative energy input increases linearly, because the electricity input rate is constant. The indoor air temperature of the rooms with electric lighting increases while the outdoor air temperature decreases. The indoor air temperature rise is caused by the thermal energy input heat from the light sources.

In the room with daylighting, the solar irradiance varies with time and weather, and the cumulative energy input saturates toward the evening. The air temperature of the room with daylighting is lower than that in the room with electric lighting in summer.

On 21st of December with much amount of solar radiation available from the window, the room air temperature increases accordingly. The 22nd of December was cloudy so that there was little increase in the room air temperature. The overall heat transmition coefficient of the window with thermal insulation boards for the rooms of electric lighting is $0.64 W/(m^2 \cdot K)$, While on the other hand, it is $6.2 W/(m^2 \cdot K)$ for the window of the room with daylighting. Since we took off the insulation boards from the windows of the rooms with electric lighting on 22nd of December, the room air temperature in the three rooms stay more or less at the same level.

Figure 4 shows the relationship between room air temperature and mean radiant temperature (MRT) in summer and winter experiments. Both are approximately the same in the two rooms of electric lighting. In the room with daylighting, MRT is higher than room air temperature. The room air temperature in the room with daylighting in summer experiment is lower than the other two rooms with electric lighting. This result shows that the windowpane as a light source is simultaneously a radiant heat source.

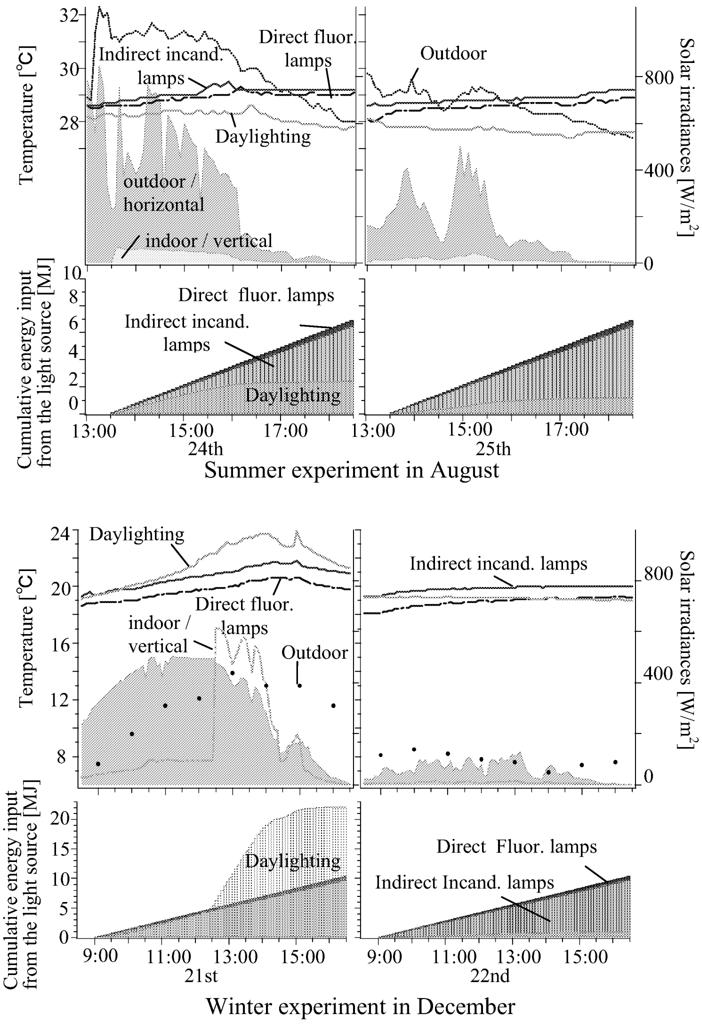


Figure 3: Measured room air temperature, solar irradiance and cumulative energy input from the light source

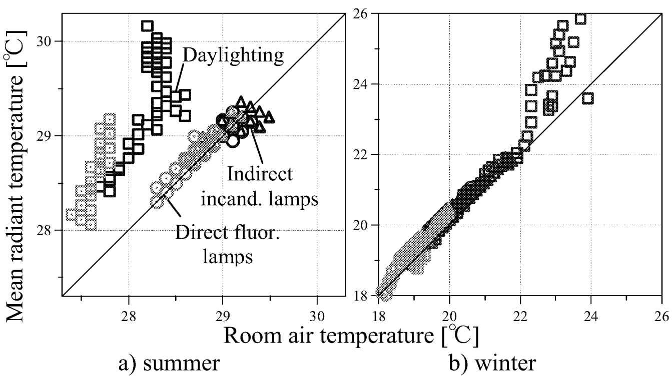
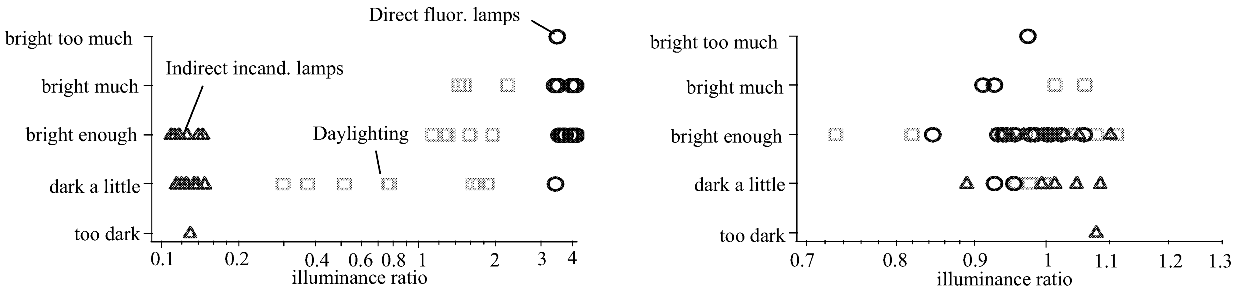


Figure 4: The relationship between room air temperature and mean radiant temperature in summer experiment and in winter experiment



a) Right after entering the room (in summer)

b) 7 minutes after entering the room (in summer)

Figure 5: The relationship between illuminance ratio and luminous sensation of the subjects

Figure 5 shows the relationship between illuminance ratio and luminous sensation of the subjects. The illuminance ratio in the graph for right after entering the room is the ratio of the illuminance that the subjects were exposed to when entering the room to the illuminance of 300lx in the corridor where they stayed for a while before entering the rooms. The illuminance ratio in the bottom graph is the illuminance at seven minutes after entering the room to the right after entering the room. The illuminance ratio of larger than unity represents a case that the subjects are exposed to more light than before.

Comparing the upper graph with the bottom graph, there are many subjects who answer "bright enough" with smaller values of illuminance ratio. Luminous sensation is regarded to be a function of the illuminance ratio.

Figure 6 shows the minimum-illuminance (MIN), to which the subjects voted the lowest acceptable illuminance, together with the maximum-illuminance (MAX) that we provided first. The values of MAX are low in the room for indirect lighting with incandescent lamps; there is little difference in the values between MAX and MIN. The illuminance in the room for direct lighting with fluorescent lamps can not be lowered below 40 lx, but the values of MIN is very much lower than those of MAX. These results suggest that lower values of illuminance than the required illuminance by the present architectural standards are acceptable. The values of MIN in the room with daylighting are almost in the same range as those in the room with indirect lighting with incandescent lamps.

Designing the luminous environment with lower illuminance level could be realized by taking into consideration the difference in the

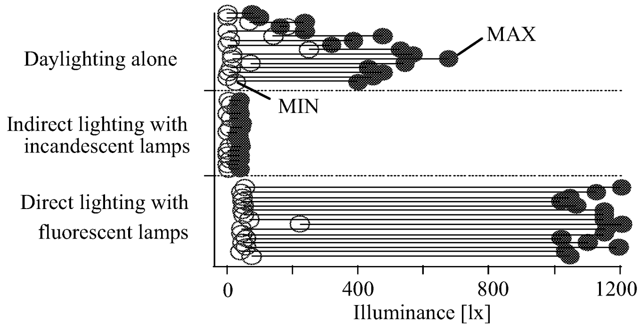
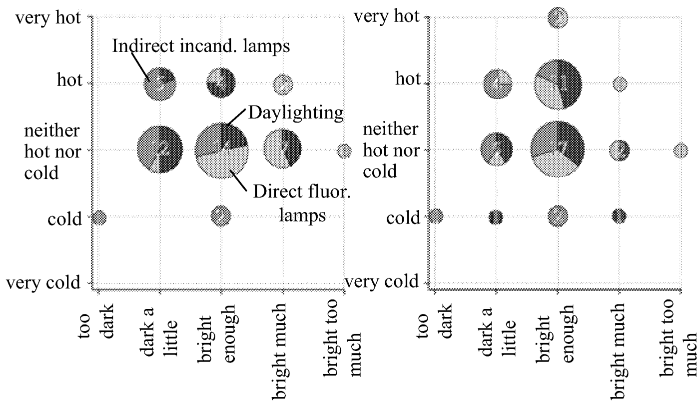


Figure 6: the MIN illuminances that each subject reported as the lowest and the MAX illuminance



a) Right after entering the room (Summer)

b) 7minutes after entering the room (Summer)

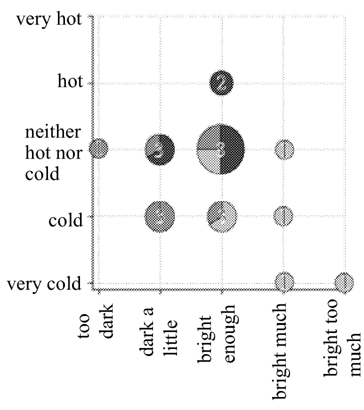


Figure 7: The relationship between the luminous and thermal sensations. The numbers in the center of the circles denote the number of subjects.

c) 7minutes after entering the room (winter) illuminance between a room space to which people spend long hours and the corridor space where they necessarily expose themselves before entering the room space.

Figure 7 shows the relationship between the luminous and thermal sensations of the subjects. In summer experiment, comparing the votes given at seven minutes after entering the room to those right after entering the room, "bright enough" increases, but "hot" and "very hot" also increase. The votes in the room with daylighting tend to concentrate rather than those in the other two rooms both in summer and in winter. In other words, there are more votes both of “bright enough” and of “neither hot nor cold” in the room with daylighting.

Figure 8 shows the relationships between the radiant exergy and sensation to heat radiation. There are two kinds of radiant exergy values for each of lighting patterns. The numbers given in the column of “light” is the radiant exergy in the range of wavelength from 0.3 to 2.5 μm available at human body. Those given in the column of “heat” are that in the range of wavelength from 3 to 70 μm. The thermal radiant exergy emitted from the light sources into a human body was calculated from the following equation.

$$X_l = f\left(X_L - X_h\right), \qquad (1)$$

where *f* is the ratio of the radiat exergy incident on the human body surface to the radiant exergy emitted from the source (the configuration factor) ; X_L is the radiant exergy emitted from the light source; X_h is the radiant exergy emitted from human body. We calculated the radiant exergy from the following equation for light-source surfaces and the human body.

$$X = \varepsilon\sigma\left\{\left(T^4 - T_o^4\right) - \frac{4}{3}T_o\left(T^3 - T_o^3\right)\right\}, \qquad (2)$$

where: ε is overall emittance of the surfaces [-]; σ is Stephan-Boltzman constant [W/(m^2·K^4)]; T_L is surface temperature [K]; and T_o is environmental temperature [K].
The radiant exergy emitted from the lighting-source surface into one square meter of human body was calculated by dividing the total of radiant exergy from the light source by human-body surface area of 1.7m^2.

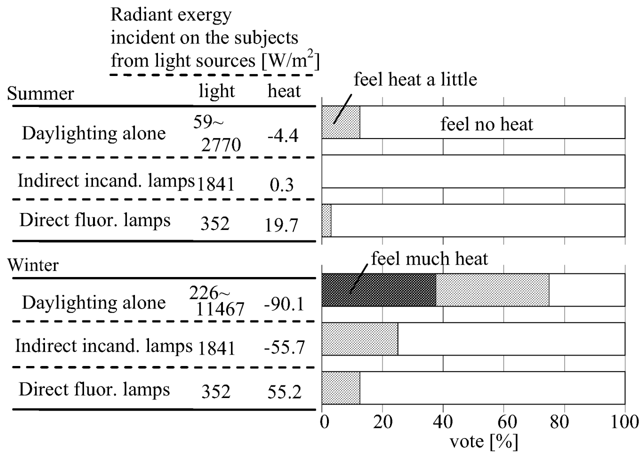


Figure 8: The relationship between the radiant exergy and sensation to heat radiation

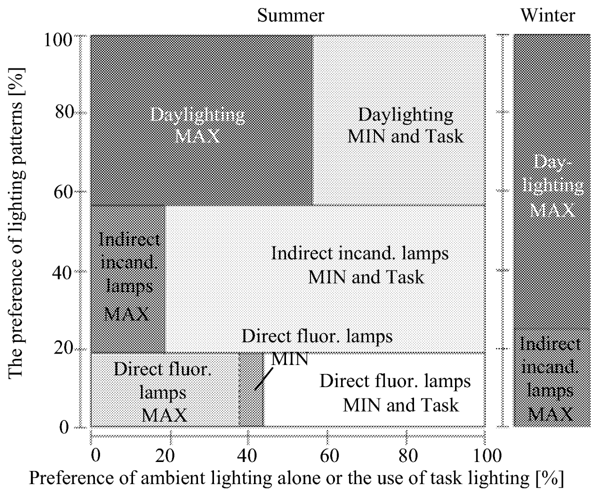


Figure 9: the preference of lighting patterns

In the case of daylighting, the values of radiant exergy as “light” from the light source are the largest. On the other hand, the values of radiant exergy as “heat” are the largest in the case of direct lighting with fluorescent lamps. Meanwhile, most of the subjects voted "feel no heat" except the case in daylighting in winter. The radiant exergy provided by daylighting has little effect on thermal sensation of the subjects in summer and much effect in winter.

Figure 9 shows the preference of lighting patterns from the subjects’ votes. The vertical axis shows the preference of the lighting patterns in percentage. According to the experiment in summer, the subjects who voted that they prefer direct lighting with fluorescent lamps was fewer than 20%. The number of subjects who prefer daylighting is more than 40%. According to the experiment in winter, there was no subject who prefers direct lighting with fluorescent lamps and more than 70% voted that they prefer daylighting. These results suggest that the illumination less dependent on electric lighting during daytime is possible.

In the case of summer experiment, the horizontal axis indicates the preference of the distribution of light. A lot of subjects prefer the combination of ambient lighting with low illuminance and task lighting to ambient lighting only with high illuminance. It is effective to make the ambient illuminance low, and to confine the high illuminance to the limited area by task lighting.

4. CONCLUSION

We conducted a series of experiments using three rooms with different lighting patterns to investigate and confirm the merit of daylighting by comparing the physical and psychological aspects of the lighting patterns examined.

Daylighting did not generate too much heat than electric lighting, but it tends to increase the mean radiant temperature.

According to the votes of the subjects, very high illuminance is not necessarily required. This suggests that we can reduce the illuminance level and thereby cut down the energy use for lighting. In our experiment, the room with daylighting was preferred by the subjects most both for luminous and thermal sensations compared to the other two rooms with electric lighting alone.

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