EXPERIMENTAL STUDY ON DISCOMFORT GLARE CAUSED BY WINDOWS PART 2

Subjective response to glare from actual windows

We conducted an experiment with actual windows in the rooms to examine the applicability of the formulae validated with simulated window to actual windows. Generally subjective evaluation in this experiment had the same tendency as our previous results with simulated window. However, both DGI and UGR were considered insufficient to predict glare sensation in all conditions. Inconsistency was shown in the case of very large source and in the difference in window orientation. Overrating background luminance in these formulae must contribute to this reason. From the multiple regression analysis it was found that "the effect of total amount of light" must not be neglected in the case of a large light source.

Keywords: discomfort glare, daylight, glare index, subjective response, window, luminance

1. Introduction

New window materials such as electrochromic glass have a great potential in controlling solar radiation or daylight transmitted through windows to a desired level so that we can benefit the brightness and the heat from solar radiation while minimizing the glare and the overheating. It becomes more important, therefore, to have a better understanding of the magnitude of the glare caused by daylight. In order to propose an appropriate glare index, from which one can predict a glare level caused by windows in a room space with ease and reasonable accuracy, further studies based on both chamber experiment and field investigation should be performed.

In the companion paper\(^1\) we presented a chamber experiment using simulated windows with artificial light sources, the objective of which was to examine the applicability of the existing glare indices, derived from the experiments using special devices, to a realistic situation; for example in actual office room conditions occupants seldom stare at one point and therefore it is important to consider the movement of worker's sight line\(^2\).

Even if a glare index formula for large sources could be obtained from a laboratory experiment, there still remain some difficulties in applying it directly to the discomfort glare from daylight through...
windows. Hence it is important to show the validity of the formula derived from an artificial large source for actual windows and to find the cause of difficulties in application.

This paper presents the method and results of a field experiment conducted in actual rooms with windows, the goal of which is to examine the applicability of the conventional formulae examined in our first paper\(^1\) to actual windows and to identify the problems in application as the basic stage for proposing an index of glare from windows.

2. Experimental method

2.1 Facilities

We used two rooms on the 11th floor of a building at Waseda University in Tokyo as shown in Fig. 1. The size and geometry of the two rooms are identical, but their window orientations are different, one is facing south and the other north. In each room there are three positions (P, Q and R), from which the subjects evaluate the glare. In each position a chair with a small desk was set and dimmable fluorescent lamps with an electronic ballast were equipped above the desk. Fig. 2 shows a schematic view of the window from one of the positions in a room. The window is divided by the frame members. The sky and the far-away buildings can be seen through the window.

2.2 Subjects

Altogether 46 students participated in this experiment as the subjects. Table 1 shows their ages and visual properties.

2.3 Procedure

This experiment was performed in December, 1989 and January, 1990. Fig. 3 shows the procedure of this experiment. Two subjects were tested at one time; one subject was asked to enter the room facing south while the other to enter the room facing north. Each subject was then asked to be seated at the desk at position P, Q or R and to read a book printed with 8 point type on each desk illuminated at 500 lx or 1000 lx. After two minutes, each subject was asked
to raise her/his head, to look at the window and to mark the glare level she/he feels with Questionnaire 1 and 2 in Fig. 4. The point where subjects had to look at was not specified. The Glare Sensation Vote (GSV) and Acceptability are defined as the values marked by the subjects on the scale shown in Questionnaire 1 and 2 respectively. The acceptability scale was recommended for subjective evaluation of indoor air quality; it provides information not only whether each subject finds the specified environment acceptable or not, but also how much acceptable or unacceptable it is.

"Percent Dissatisfied" is the percentage of the subjects who judge the glare to be "not acceptable", i.e., less than zero of Acceptability. After evaluation of the glare each subject was asked to evaluate the brightness on the desk, because we wanted to know the effect of the glare on the brightness sensation perceived at the time when the subject looked at the desk again. However, the results of these questionnaires are beyond the main scope of this paper, and not presented here. See reference (5).

Each subject repeated the test at three different evaluation positions with two different illuminances on the desk (500 lx and 1,000 lx) in the two rooms (total of twelve conditions). Since some subjects appealed that the particular parts seen from the window caused the glare, we added one more questionnaire asking if there was any part causing the glare after the middle of this series of experiment. The cases when direct sunlight reached the position occupied by the subjects were excluded from the analysis.

During the courses of the experiments the luminances of each center of nine portions on the window shown in Fig. 2 were measured by an experimenter who sat behind a subject to operate a luminance meter over the subject's shoulder. The vertical illuminance at the eyes, horizontal illuminance on the desk and ambient temperature were measured every ten seconds automatically. The cases when the standard deviation of the vertical illuminance was above 10% of average were excluded from the analysis because of too much fluctuation in the window luminance.

2.4 Glare Indices to be examined

A number of formulae evaluating discomfort glare have been proposed in several countries. In our companion paper we referred to Daylight Glare Index (DGI)7, BRS Glare Index (BRS-GI)8, and Unified Glare Rating (UGR)9, because DGI was the only one index applicable to large sources, because BRS-GI was the root of DGI and because UGR was a modified form of BRS-GI due to mathematical inconsistency in BRS-GI. Although BRS-GI could not be applied to a large source, the rest of two indices, DGI and UGR had a good correlation to Glare Sensation Vote (GSV) in central vision with simulated window. DGI and UGR are defined in the following equations.

\[
    \text{DGI} = 10 \log 0.478 \sum \frac{L_s^8 \Omega^8}{L_r + 0.07 \Omega^8 L_s} \tag{1}
\]

\[
    \text{UGR} = 8 \log 0.25 \sum \frac{L_s^4 \theta}{E_r \sum p^2} \tag{2}
\]

where \(L_s\) is the luminance of each glare source in the field of view \([\text{cd/m}^2]\); \(\Omega\) is the solid angular
subtense of the glare source at the eye \([\text{sr}]\); \(L_o\) is the background luminance \([\text{cd/m}^2]\); \(\Omega\) is the solid angular subtense of the source modified for the effect of the position of its elements in different parts of the field of view\(^\text{[3]}\); \(p\) is the position index\(^{[3]}\); \(E_i\) is the vertical indirect illuminance \([\text{lx}]\) at the eyes.

Although there is another method called Visual Comfort Probability method (VCP)\(^{[11]}\) which has been developed in the United States, we decided not to examine this method in the present paper: one of the reasons for this is that this method was concerned with the BCD (between comfort and discomfort) brightness while we used Glare Sensation Vote, a modified scale of the Hopkinson's Glare criterion, and another was presented in reference (12).

3. Calculation of Daylight Glare Index and Unified Glare Rating from measured physical quantities

Table 2 shows the solid angle and the range of vertical illuminance at the eyes measured in each position. Fig. 5 shows the cumulative frequency of the luminance of the windows facing south and north. We calculated the average window luminance from the luminances at the center of each of nine portions as shown in Fig. 2(a) and their respective solid angles. Table 3 shows the luminance of each portions in the window. The background luminance \(L_o\) \([\text{cd/m}^2]\) was calculated from the following equation.

\[
L_o = \frac{E_v}{\pi} \frac{\sum_{i=1}^{p} L_i \Phi_i}{1 - \sum_{i=1}^{p} \Phi_i}
\]

where \(L_i\) is the luminance at the center of each of nine portions in the window \([\text{cd/m}^2]\); \(\Phi_i\) is the configuration factor of each nine portions from the eyes \([-]\); \(E_v\) is the vertical illuminance at the eyes \([\text{lx}]\).

The air temperature in the rooms were maintained at 18-21°C throughout the experiment.

Two problems arose when we tried to calculate DGI or UGR of the actual window. One problem is whether the window should be treated as one window or multiple windows in such a case that a window has vertical and horizontal frames, or in such a case that the view from the window consists of the sky.

Table 2 Solid angle of the window and vertical illuminance in the experiment using actual window

<table>
<thead>
<tr>
<th>Room</th>
<th>Seat</th>
<th>Angle [sr]</th>
<th>Illuminance [lx]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window</td>
<td>P</td>
<td>0.622</td>
<td>710 (\sim) 9640</td>
</tr>
<tr>
<td>south</td>
<td>R</td>
<td>0.109</td>
<td>200 (\sim) 2620</td>
</tr>
<tr>
<td>Window</td>
<td>P</td>
<td>0.622</td>
<td>720 (\sim) 2960</td>
</tr>
<tr>
<td>north</td>
<td>R</td>
<td>0.109</td>
<td>160 (\sim) 1270</td>
</tr>
</tbody>
</table>

Table 3 Luminance of the center of each nine portions

<table>
<thead>
<tr>
<th>Point</th>
<th>South</th>
<th>North</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1300</td>
<td>21500</td>
</tr>
<tr>
<td>2</td>
<td>1200</td>
<td>15000</td>
</tr>
<tr>
<td>3</td>
<td>1400</td>
<td>26000</td>
</tr>
<tr>
<td>4</td>
<td>1100</td>
<td>21500</td>
</tr>
<tr>
<td>5</td>
<td>1100</td>
<td>18000</td>
</tr>
<tr>
<td>6</td>
<td>1000</td>
<td>18000</td>
</tr>
<tr>
<td>7</td>
<td>1000</td>
<td>3000</td>
</tr>
<tr>
<td>8</td>
<td>250</td>
<td>3000</td>
</tr>
<tr>
<td>9</td>
<td>300</td>
<td>3000</td>
</tr>
</tbody>
</table>

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the ground and the adjacent buildings. In calculation of DGI the window could be divided into two, six or nine portions by the frames or the skyline as shown in Fig. 2. We followed a calculating procedure given by Chauvel et al., which in the luminance Lw in the second term of the denominator of equation (1) is assumed to be the average luminance of the window, ω in the second term of the denominator to be the total solid angle of the window while Lw and D in the numerator to be the luminance and the modified solid angle of each patch of the visible sky, the obstructions and the ground seen through the window, respectively. Therefore Σ in equation (1) means summing up the terms only in the numerator. The calculated value of DGI became greater as the window was subdivided into more portions because of the mathematical inconsistency of the DGI. However, the difference in DGI obtained from between nine and two portions was found as small as about 1. The value of UGR is independent of the number of subdivided portions.

The other problem is where the point of sight is assumed to be fixed. In actual spaces the occupants always change their view points. Therefore it is hard to determine one value of the modified solid angle as a function of the position index and hence undecided value of DGI. Fig. 6 shows the relationship between DGI values calculated by two ways; one is that the point of sight is assumed to be at the center of the window and the other at the eye level. There is a difference because in the former the sight of the subjects is directed to the sky and in the latter it is to far-away buildings. This problem also lies in calculating UGR.

Meanwhile we used DGI and UGR calculated for the window subdivided into six portions assuming the point of sight at the eye level.

4. The relationships between GSV and DGI or UGR

Fig. 7 shows the relationships between DGI and UGR calculated in the cases of positions P and R in both rooms, in order to show the influence of the apparent size of the window and the orientation of the window. Each linear correlation is found very high. There is some difference in regression lines between position P and R, namely, the apparent sizes of the window. With respect to the orientation of the window a little difference in regression line is found in position P while no difference in position R.

Fig. 8 shows the relationship between DGI and GSV. Founding the plots scattered very much, in the figures to follow plots were made in a such a way that the axis of abscissa was classified in a certain range to show the mean value of each plot for each range with circle marks. The size of each circle represents the frequency in each range.
4.1 The influence of window size
Fig. 9 shows the relationships between DGI and GSV for the window facing south in the positions P, Q and R in the case of 1,000 lx of task illuminance. It appears that these results are almost similar to the results from the simulated windows; GSV by the subjects is smaller than that predicted by Hopkinson by 1 in GSV scale. In position P the subjects voted higher value of GSV than in position Q and R. A possible reason for this may be that the solid angle of the window from position P is considerably greater than that of the simulated window and that from position Q and R. The similar tendency was seen in the case of the window facing north. The sizes of the window caused little difference when UGR is used instead of DGI.

4.2 The influence of the orientation of the room
Fig. 10 and 11 show two examples of the relationships between DGI and GSV for the window facing south and facing north in position P. GSV for the window facing north is a little
smaller than that for the window facing south. Fig. 12 shows an example of UGR and GSV for the windows facing south and north in position P. Against UGR instead of DGI the difference in GSV between south and north becomes more obvious because higher values of UGR are obtained as seen in Fig. 7.

One possible reason for this disagreement by the orientation of the room is the difference in background luminance between south and north. The window facing north brought about a higher value of DGI or UGR than the window facing south under the condition of the same luminance and the same apparent size of the window, because the window facing north gave lower surrounding luminance, namely lower background luminance excluding the window as can be seen in Fig. 13.

Fig. 14 presents the relationships between the luminance of windows and GSV for the window facing south and north. The relationships between GSV and the luminance of windows appears consistent with each other, though the GSV for the window facing north is only slightly greater than the window facing south for the same window luminance. This means that the surrounding luminance have only small influence on the glare sensation. The influence of the surrounding luminance on the resultant values of both DGI and UGR may be too large.

5. Problems of DGI and UGR

As mentioned above neither DGI nor UGR can be applied to all conditions in this experiment, although GSV for the windows facing south in this experiment seems to agree with the GSV from the simulated window. From the results mentioned in 4.1 neither DGI nor UGR can explain the influence of the window size. Moreover from the result mentioned in 4.2 the influence of the surrounding luminance may be overrated in both DGI and UGR. To identify the characteristics of DGI and UGR formula, we calculated the values of DGI and UGR for various sizes of the light source under the condition of 10 000 cd/m² of source luminance and either 20 or 200 cd/m² of the surrounding luminance. The results are presented in Fig. 15.

5.1 The influence of window size

As the source size increases the rate of increase in DGI becomes small and at a certain source size DGI reaches maximum and then decreases. We reviewed Hopkinson’s experimental results and found that in the cases of 150 cd/m² of surrounding luminance GSV always increased with the increase of the size of source. Moreover we found that his experimental results themselves included an inconsistency in the
case of full visual field of source. Those facts caused DGI's inconsistency regarding the source size.

5.2 The influence of background luminance

UGR increases as the source size increases, while the influence of the surrounding luminance is constant, namely independent of the source size. This fact is consistent with what was mentioned in 4.2; it must be an obstacle when UGR is applied to a large source. The influence of surrounding luminance on DGI decreases as the source becomes larger, but the rate of decreasing may still be too small.

In our previous paper we obtained the results that the denominator of DGI did not have to be replaced by the average luminance of visual field even if this replacement was theoretical. If the denominator was replaced by the average luminance of the visual field the difference in DGI-GSV relations would become apparent among three source sizes of 0.026 sr, 0.052 sr and 0.102 sr. Therefore we tentatively supported Hopkinson's empirical modification for the denominator of DGI. However through the results of our experiment with the actual window has brought about another possibility; the ratio of the exponent of the source luminance to that of the background luminance could be a function of source sizes and/or source luminances. The modification by Hopkinson was made under the assumption that the ratio of the exponent is constant regardless of the source size or the source luminance.

Most of the glare formulae have the term including the source luminance \( L_s \) and the background luminance \( L_b \). The ratio of the exponent of the source luminance to that of the background luminance are constant; 1.6 in BRS-GI (\( \omega < 0.027 \text{ sr} \)) and in DGI, 2.0 in UGR (the range of \( \omega \) is not specified) and 2.3 in DGR (\( \omega < 0.13 \text{ sr} \)). In BRS-GI and UGR the surrounding luminance is used as the background luminance and in DGI the modified surrounding luminance is used. While in GDR the average luminance of visual field including light source is used as the background luminance. Tabuchi et al. (\( \omega < 0.13 \text{ sr} \)) gave more weight to the background luminance, i.e., the ratios were set 1.3 by the method of adjustment and 1.5 by the method of direct evaluation\(^{14,15}\). All of them except DGI were proposed for rather small sources with rather low luminance. The ratio of the exponent for large sources would possibly be dependent on the source luminance.

6. The influence of pre-adaptation luminance level

In this experiment each subject made evaluation immediately after she/he raised the head and looked at the window. While performing the tasks, the adaptation luminance level of the eyes mainly depends on the task luminance. The adaptation luminance levels of the eyes before looking at the window are 220 cd/m\(^2\) and 110 cd/m\(^2\) in respective cases of task illuminance assuming the task surface to be idealy diffuse with reflectance of 0.7. Fig. 16 shows the relationships between the average luminance of the window and GSV, where no difference in GSV is found between 1 000 lx and 500 lx of task illuminance. One of the reasons for this may be that the difference of adaptation luminance level of the eyes between in the cases of 1 000 lx and 500 lx of the task illuminance was too small to see the influence of pre-adaptation level. This agrees with the results of a study by Inoue et al.\(^{11}\). However the surrounding luminance in the case of 1 000 lx of task illuminance tends to be higher than that in the case of 500 lx as shown in Fig. 13, because the desk top was illuminated by the fluorescent lamps equipped above the

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desk. Therefore the luminance of visual field including the window in the case of 1 000 lx of the task illuminance was higher than that in the case of 500 lx. To identify clearly the influence of the pre-adaptation luminance level we should have made the pre-adaptation luminance level independent of the surrounding luminance.

7. A possible glare formula for large sources

In order to assess discomfort glare from windows in actual conditions we should consider three effects; the contrast in a visual field, the transition of adaptation luminance level of the eyes, and the total amount of light coming into the eyes. The latter two effects, which are not considered in DGI and UGR, should be functions of time, as time goes on “the transition effect” decreases and “the effect of the total amount of light” increases.

Here we try to demonstrate how the relationship between the three effects on GSV could be expressed using the measured results of the present field experiment with the actual window. We assumed a formula in the following equation.

\[ GSV = f \text{ (contrast effect, transition effect, effect of the total amount of light)} \]

\[ GSV = a \times \log \frac{L_{sw}^{1.5} \phi_{ga}}{L_{sw}} + b \times \log \frac{L_f}{L_{sw}} + c \times \log E_v + k \]  

where \( L_{sw} \) is surrounding luminance (cd/m\(^2\)), \( L_f \) is average luminance of the visual field (cd/m\(^2\)), namely \( L_f = L_o \phi_s + L_{sw} \phi_{su} \). \( \phi_s \) and \( \phi_{su} \) are configuration factor of window and the surroundings, respectively, and \( L_{sw} \) is pre-adaptation luminance (cd/m\(^2\)), namely the average luminance of the visual field before looking at the window, \( E_v \) is illuminance on the vertical plane at the eye (lx) and \( k \) is constant. We calculated \( L_f \) and \( L_{sw} \) as follows: \( L_f = E_v / \pi \) and \( L_{sw} = \text{task illuminance (lx)} \times \text{mean reflectance of the task plane} / \pi \). The coefficients \( a \), \( b \) and \( c \) are considered to be functions of the above mentioned three effects, but to simplify the analysis we assume that these coefficients are constant in the range of this experiment.

Using multiple regression analysis we determined the coefficients \( a \), \( b \), \( c \) and \( k \) from the experimental data in the case of window luminances of above 1 000 cd/m\(^2\) (number of data \( N = 440 \), multiple correlation coefficient \( R = 0.52 \)) as in the following equation.

\[ GSV = 0.36 \times \log \frac{L_{sw}^{1.5} \phi_{ga}}{L_{sw}} + 1.13 \times \log E_v - 4.12 \]  

\[ = \log \frac{L_{sw}^{1.5} \phi_{ga}}{L_{sw}} - 3.6 \]  

"The total amount of light" has the largest effect on GSV as can be seen from equation (5). It is found also by comparing the standard regression coefficients, “The transition effect” did not appear in this equation from the results of F-test. It might be caused by the fact that the surrounding luminance was dependent on the task luminances as mentioned in Section 6.

Coefficients \( a \), \( b \) and \( c \) may vary with the lighting conditions. However, these coefficients can be regarded constant within a certain limited range of conditions and it is found that “the effect of total amount of light coming into the eyes” can not be neglected in the case of a large light source. In a further study we should identify in what range each of three effect influences most the glare sensation. Fig.17 shows the relationship between GSV predicted from equation (5) and GSV judged by subjects.

8. The other possible difficulties in evaluation of glare from window

As the multiple correlation coefficient is rather low, some
problems of evaluation of glare from windows may still remain. One of them is the movement of the line of sight. Several subjects claimed that a specified part in the window caused glare such as bright mass of cloud seen through the window facing south and white envelope of the buildings seen through the window facing north.

9. Percent dissatisfied and glare sensation vote

Fig. 18 shows the relationship between GSV and Acceptability. There is no significant difference between the windows facing south and facing north, between 1000 lx and 500 lx of task illuminance and among three positions in the room. Therefore we drew the relationship between GSV and Percent Dissatisfied using all experimental results as shown in Fig. 19. This relationship obtained from the experimental results with the actual windows is almost similar to that with the simulated window.

10. Conclusions

To examine the applicability of the conventional formulae to actual windows and to identify the problems in application, we conducted an experiment using actual windows and found the following conclusions:

1. Subjective evaluation in this experiment, especially evaluation for the window of 0.235 and 0.109 sr facing south, had the same tendency as the results from our experiment using simulated windows.

2. Both DGI and UGR were insufficient to predict glare sensation in all conditions. Inconsistency was shown in particular in the cases of window of 0.622 sr and window facing north. The weight of the background luminance for calculating either DGI or UGR formula is considered to be too large. New formula is required in which the ratio of exponents is dependent on the range of conditions and it is important that the range of its application should be defined.

3. Multiple regression analysis showed that "the effect of total amount of light" cannot be neglected in the case of a large light source. "The transition effect" did not appear significant in the range of our experiment.

4. The problems with actual windows especially on the distribution of the luminance within the window surface and line of sight relative to the window, should be investigated furthermore.

5. No significant difference was found in the relationship between GSV and Acceptability between the windows facing south and facing north, between 1000 lx and 500 lx of the task illuminance and among three positions in the room. The relationship between GSV and Percent Dissatisfied introduced from the all conditions was found almost similar to that with the simulated window.

Acknowledgement

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和文要約

1. 緒 言

最近、ガラス材の開発などにより昼光照明の制御が可能になりつつあり、窓面による不快グレアの評価が重要になってきている。そのため実験室実験とともに実空間の測定が必要と考えられる。前報1)では模擬窓を用いた実験により、従来のグレアインデックスの相対に近い状態における大きな光源への適用性を調べた。

人工の模擬窓から求めた大きな光源に対するグレアインデックスをそのまま実際の窓からのグレアの評価に適用できるかどうかについては疑問が残る。本報では窓面からのグレアの評価値の提案のための基礎段階として、実空間の窓を用いた現場実験を行い、従来のグレアインデックスの適用性を確認し、問題点を明らかにした。

2. 実験方法

2.1 実験装置 実験は早稲田大学 51号館 11階の南側、北側に面する同じ形状の 2 室において行った。実験室の平面および断面を図-1に示す。被験者は図-1各 P, Q, R の各点において窓面に正対して椅子に座る。


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顔をあげ、窓面のまぶしさについて、図-4に示した質量
1と質量2に示したものを被験者のがこの一連の操作
を、南北2室、3測点、機上照明2段階、計12回行っ
た。実験中、図-2に示す窓内の9点の輝度、窓の位置
の鉛直面方向、機上照明、室間の気温を測定した。
2.4 検討したプレインディックス 前報の模擬窓で適
用の可能性が示された DGI と UGR について検討した。

3. 測定された物理量と DGI、UGR の計算
表-2に表の位置の鉛直面方向の窓の垂直角を示す。
表-5は窓面輝度について累積出現頻度を示したもの
で、表-3には窓内各点の輝度について示した。室温は
実験中18〜21℃であった。
実際に DGR、UGR を計算しようとすると2つの問
題が見受けられた。
まず、窓面がサッシュや棟によって区切られ、さらに
窓内に空部分と建物部分がある場合の窓面の分割方法の
問題がある。DGI では Chauvel らにより作成したダニ子部
分だけ分割したそれぞれの値を加算して求めたところ9
分割が2分割より約10段階大くなった。UGR では分割
数による差はなかった。
もう1つの問題は、居住者の視線は常に近くのもの、す
なわち空間全体を評価することができるものである。
図-6に示すように視点を窓の中心とした場合と窓の上
下を同じと仮定した場合の DGI の値はやや異なる。この問題につい
ては UGR でも同様である。

以下では以下使用する DGI、UGR とも窓面を
サッシュで区切った6分割とし、視点を窓の上と下とした。

4. DGI、UGR と GSV
図-7に実験から計算された DGI と UGR の関係を
示す。それぞれ直線回帰され、回帰直線は立体角の大き
さにより異なり、また立体角の大きい場合には南と北の
面で差が見られた。
実際の窓を用いた全実験の結果を見ると図-8の南側
の机上1000lxの場合を示すように申し告げに大きな散
らばりがあったので、横軸をある範囲ごとに区切りその
範囲の平均値を示し、プロットの大きさでその範囲の出
現頻度を示すことによった。
4.1 窓の大きさの影響 模擬窓との比較のため、機上
面1000lxの場合について、南側の DGI と GSV の関
係を図-9に窓面大きさ別に示す。全体としては模擬窓
による結果に非常に近く、Hopkinson による予測値よ
り GSV で1程度小さい。立体角の大きい位置 P での
GSV がやや高くなっており、同様の傾向が北側でも見ら
れた。横軸を UGR にするときの差はやや小さくなった。
4.2 窓面の方位 DGI と GSV の関係も南側と北側で
比較すると南の方が北より GSV が大きい。例として図
-10, 11 に位置 P, R について示す。また UGR と
GSV の関係においては図-12のように位置 P では北側
の UGR に大きな値が出現し、南北の差はさらに顕著とな
る。
この原因の1つとして、図-13に示すように同じ窓
面輝度、同じ窓の大きさに対して南側の方が光源を含ま
ない背景輝度が高くなることが挙げられる。図-14に
示すように窓面輝度と GSV の関係においては位置 Q,
R では北側の方がわずかに高く DGI, UGR の式では周
面輝度を適当評価していると考えられる。

5. DGI、UGR の問題点
DGI、UGR とともに南側で比較的立体角が小さい位置
Q, R の場合においては模擬窓の結果と異なり一致した
が、適用できない範囲がある可能性も示された。一致し
ない結果が現れる原因について検討した。
5.1 光源の大きさ 図-15に示すように DGI は立体
角が大きくなると増加するが、ある立体角以上になると
増加がゆるやかに減少する。Hopkinson の実験データを再検
討してみると、背景輝度 150 cd/m² では GSV が立体角
の増加に伴って常に増加していた。また、実験データ自
体が光源が視野全体の場合は問題していた。これらのこ
とから、DGI の光源の大きさに関する矛盾の原因となっ
ていると考えられる。
5.2 背景輝度 UGR は光源の立体角の増加にした
gateで増加しているが、背景輝度の影響は光源の大きさ
によらず一定となっている。これは UGR が大きい
光源で適用する場合の問題となるだろう。一方 DGI で
は背景輝度の影響は光源の立体角の増加をともに減少す
るが、本実験結果からみとみその減少の割合が必ずしも
十分ではないと考えられる。
前報では DGI の分母を視野の平均輝度に代えると3
つの光の大きさの間に差を生じてしまう事から、
Hopkinson の実験式をとりあえず支持した。しかし、
実際の窓の結果から背景輝度に対する Hopkinson の
修正も十分ではないことがわかった。背景輝度と光源輝
度のべき指数の比を窓面の大きさ、光源の輝度によって
変化させることも考えられる。
多くのグラフの式は光源輝度と背景輝度の式を含んで
おりそのべき指数の比は式によって1.5から2.3で一定
である。DGI を除いていずれの指標も比較的低い輝度
の小さい光源のために求められたものであり、光源の大き
さ、輝度によって背景輝度の影響の大きさが変わる、
すなわちべき指数が変化すると考える必要があるだろう。

6. 前照輝度の影響
本実験では機上を観ている状態から窓を見た直後の
評価を行っているので、前順応輝度は机上面照度×機上面の平均反射率/αで示すことができると考えられる。
どの位置においても窓面平均輝度と GSV の関係に機上面照度の影響は現れていない。一例を図-16 に示す。
この原因の一つとして前順応輝度の差が影響が現れるほど大きくなかったことが考えられ、これは井上らの結果と一致する。しかし、機上面を頭上から照らしているので図-13 に示すように機上面 1000 lx の場合の方が 500 lx の場合よりやや高い周囲輝度となっており、窓面含む視野の平均輝度も高くなってしまったためかもしれない。

7. 大きい光源に対するグレア評価のための考察
実際の条件での窓からの不快グレアを評価するために「視線内の対比」、「順応輝度の過渡」、「眼に入る光の総量」の 3 つの効果を考えてみた。後の 2 つは DGI, UGR では考慮されていないが、時間の関数でもあり、時間の経過とともに「順応輝度の過渡」による効果は減じ、「光の総量」効果は増すであろう。
本論文では単純にこの 3 つの効果を (4) 式のように仮定してみた。係数 a, b, c それぞれがそれぞれの効果の大きさを反映する関数であるが本実験の範囲では一定であると考えて窓面平均輝度 1000 cd/m² 以上の場合について重回帰分析による解析を行った。結果は (5) 式のようになった。分散分析の結果、「順応輝度の過渡」による効果が現れなかった。これは機上面を頭上から照らしているので前順応輝度が高くなると周囲輝度も高くなってしまうことの影響があると考えられる。標準化した係数の比較でも「光の総量による効果」が大きかった。
係数 a, b, c はそれぞれの効果の大きさによって変化すると考えられが、限られた範囲では一定と考えられる。よって、大きな光源の場合「光の総量効果」は無視できないと考えられる。

8. 窓面グレアの評価法
重回帰式でもなお重相関係数が小さく、窓からのグレアの評価にはまだ問題があるだろう。被験者の中には窓内の特定の場所からグレアを感じると訴える者もいた。

9. 不快率と GSV
図-18 に GSV と事務作業空間としての許容度 (Acceptability) の関係を示す。この関係は窓の大きさ、方位、機上面照度によらず一定であった。
そこで図-19 にはノーマルから求めた GSV と不満者率 (Percent Dissatisfied) の関係を示す。実際の窓から得られた関係は、人工光源を用いた場合とよく似ている。

10. 結論
実際の窓を用いた実験により以下のような結果を得た。
(1) DGI-GSV, UGR-GSV の関係は全体的には模擬窓と似た傾向が示され、特に南向きの小さい窓では模擬窓の結果に近かった。模擬窓の結果に近かった。
(2) DGI、UGR とも、0.622 sr の光源や、北側の窓において等しい結果が現れ、適用できない範囲があることも示された。これは DGI、UGR 式における背景輝度の過渡の重みに原因があると考えられ、それぞれのベキ指数の比が条件によって変化することを考慮し、適用範囲を明確にする必要があると考えられた。
(3) 重回帰分析の結果より大きい光源では「光の総量」による影響が無視できないことが示された。「順応輝度の過渡」による影響は本実験範囲では現れなかった。
(4) 実際の窓に関しては、さらに窓内輝度分布と窓に対する視点の位置の問題を明らかにしなければならないと考えられる。
(5) GSV と、不満者率をスケール化した許容度の関係は窓の大きさなどの条件によらず一定だったので申告全体から GSV と不満者率の関係を求めた。これは模擬窓の結果に近かった。