Paper

“Impression of Brightness of a Space” Judged by Information from the Entire Space

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ABSTRACT

A new evaluation method for “brightness of a space” was investigated. First, we have examined the basic relationship between arrival direction of the light and brightness by using the full-scale model. The results are as follows: 1) Brightness changed due to the subject’s action, even if the condition of the light was absolutely the same. 2) The light from horizontal direction is more effective for brightness. 3) Brightness changed due to the balance of arrival direction of the light, even if the total amount of the light is same. Next, the measurement tool for obtaining data of the light that comes from all directions was developed. We examined two effects of “quantity of the light” and “the spatial balance of the light” on the brightness of the space using got value from the tool. As a result, we discovered that former can be explained at the value which horizontally integrated 360° in the weighting of (1+cosθ)/2 and latter can be explained at the angle of visibility and directional diffusivity.

KEYWORDS: brightness of a space, luminance distribution, directional diffusivity

1. Introduction

Today, a generally used index for lighting design is horizontal illuminance defined by JIS 13 in 1976 and by JIES under “indoor lighting standard” 9 in 1999. In 2000, color rendering and glare indexes were added to lighting standard under “ISO/CIE Lighting of Indoor Work Places” 10 issued by ISO and CIE, yet index relating to the brightness of a room is still defined by horizontal illuminance.

Since horizontal illuminance represents the amount of light radiating on a desktop (or floor), this index is appropriate for a lighting environment for desktop tasks. This is an important index from the perspective of workability and safety. However, the purpose of lighting design is not only aimed at securing brightness on a sheet of paper placed on a horizontal plane, but also at controlling brightness of a three-dimensional space according to the purpose of the room and preference of the user. Hence, horizontal illuminance alone is not sufficient for light designing.

The insufficiency of horizontal illuminance is also evident from a survey conducted to people engaged in light designing professions 6. Some have said, “While securing horizontal illuminance is important, this index alone will not suffice. In fact, it is complemented by our experiences and intuitions.”

In former years, due to lack of technology and funds, the main focus was placed on securing minimum brightness or fulfilling visual conditions to pursue desktop tasks, thus the existing standard did not cause inconveniences and the concern toward excess lighting was minimal. However, today, visual conditions are fulfilled with the advancement of technology and people’s lives becoming affluent. It is necessary to focus on the quality of lighting environment instead of merely seeking brightness. Lighting design to achieve proper brightness according to the purpose and architectural plan is demanded, and we must review whether or not the existing indexes meet the current needs.

2. Previous studies and status of this study

There are many studies aiming at clarifying “impression of brightness of a space.” All of these studies do not deal only with two-dimensional plane such as a desktop but rather with impressions in three-dimensional space that expands before one’s eyes. However, the visual fields by which the impressions are judged vary.

Nakamura, et al clarified the influence of luminance distribution within visual field on impression of brightness by model test, whose condition corresponds to 1 in Figure 1 8. Loé, et al proposed that impression of brightness can be judged by the mean luminance of 40°-degrees (upper 20 degrees and lower 20 degrees) visual field by experiment under condition 2 in Figure .1
(hereafter, “B40 mean luminance”) by Ishida, et al., although the direction of the observer’s seat was fixed, conducted experiments in an actual space under condition 3 in Figure 1, where the target is a three-dimensional space. Ishida explained spatial impression of brightness from the impression of quantity of light (hereafter “virtual luminance distribution method”) by Shinoda, et al. defined the color mode boundary luminance to be the luminance at which the impression changes from nonluminous object color to light source color, and explains that this change corresponds to the impression of brightness of a space under condition 3.

Figure 1 The visual field of target for evaluation of brightness

The reason for these past studies to target at different visual fields although dealing with the same subject, i.e., “impression of brightness of a space,” is the difference in the assumed circumstances. 1 and 2 represent the condition where the entire room is viewed from the entrance and thus are effective in grasping one’s first impression, which is easily memorized, immediately after entry. 3 represents the condition where the room is furnished with sofas, chairs, and etc. and the seating position is roughly specified.

On the other hand, 4, which is the experimental condition for this study, is on the premise that the observer will look around the entire space. This condition is based on the idea that when using a space over a long term, the eyes will unconsciously move in various directions and will hardly ever be fixed to a single direction. In addition, although the openings of the room (i.e. doors and windows) are fixed unless a major renovation is conducted, furniture arrangement is not fixed but can be changed. Based on this perspective, a comprehensive and universal judgment on the impression of brightness of a space that is not affected by conduct or seating position cannot be made only by observation made at the entrance nor with fixed seating position and eye direction.

As for studies that consider total lighting while observer is inside the space, Lynes and Gutorov proposed scalar illuminance and cylindrical illuminance, respectively. Scalar illuminance is an index that describes the quantity of light in a space and is a comprehensive, not spatially weighted, physical quantity. However, the relationship between this quantity and psychological quantity is not clarified. As to the mean cylindrical illuminance, light of high directivity coming from the overhead is not taken into account. The study deals with physical quantity of lights in the overall space and the mean cylindrical illuminance corresponds with impression of brightness to some degree. Yet, several problems must be resolved to achieve a perfect correspondence. Further, only a single value is obtained in total and thus there is no indication of how brightness by direction affects the judgment on the impression of the entire space.

In Figure 2, studies are presented in order of width of the targeted visual field. In order to clearly distinguish the various interpretations of “impression of brightness,” this study adopts the following definitions/classification.

Figure 2 Definitions of brightness

- Impression of brightness of a light source: Impression of brightness that is dependent on the light quantity of the light source itself
- Impression of brightness of a visual field: Impression of brightness judged by information obtained within the visual field when facing one direction
Impression of brightness of a space: Impression of brightness judged by information collected from the entire space in which the observer exists

Studies relating to “impression of brightness of a light source” include Fechner’s law (impression of brightness is proportional to logarithm of luminance)\(^{11}\) and Stevens’ law (impression of brightness is proportional to the power of luminance)\(^{12}\). These two studies attempt to evaluate luminance of a light source in the dark. However, these studies do not take into account the effect of background luminance, which may change psychological quantity. Bodmann, et al studied impression of brightness of a light source with consideration of background luminance and introduced a scale for impression of brightness\(^{13}\).

Studies relating to “impression of brightness of a visual field” include Lee’s B40 mean luminance and a study by Nakamura. Studies by Ishida and Shinoda are also classified as “impression of brightness of a visual field” since the seated observer does not look around the entire room including one’s behind, although the eye direction is not fixed at a single direction. As described earlier, these studies can be applied in the case where the usage of the room is specified and short term.

Under the above classification, the target for judging “Impression of brightness of a space” is the entire space, and thus, the target visual field is 360 degrees. If so, our study falls under the third group. Although the past studies that we classified into the second group, “impression of brightness of a visual field,” must have naturally dealt with the impression of brightness of a space, the significance of this study lies in distinguishing these two groups. The cognitive process in the brain is not identical if the visual field is different. When a human being is inside an architectural space and tries to understand the space, one will look around the entire space or memorize the brightness of all walls over a long term even when one does not look around the entire space at initial entry. In this respect, one judges the impression of the entire room by combining the information obtained from all directions of the space. In other words, if the total impression is derived from the accumulation of a number of visual information, the two groups, “impression of brightness of a visual field” and “impression of brightness of a space,” are of a stratified structure. Further, it is impossible to simultaneously grasp and vividly retain all information of the entire space. The more information one is exposed to, the broader becomes one’s observation. In other words, if the target of judgment changes, then one’s understanding of the information changes. This occurs when the target visual field is widened, but we believe this is also related to the length of one’s existence in the space.

A long-term existence in a space will increase the amount of information since one will have a chance to see more objects in the space. A distinction between “impression of brightness of a visual field” and “impression of brightness of a space” is made, since we believe that the concept “impression of brightness of a space” is necessary when judging a space where a single person will use for a long term, such as a living room in the home.

In this study, we will first propose the idea of “impression of brightness of a space” which takes into account observing the entire space from the inside. Further, we will clarify the observer’s judging mechanism since existing indexes are not sufficient for this newly defined “impression of brightness of a space.”

3. Luminance distribution measurement tool using fish-eye lens and digital camera

Detailed luminance information of the entire space is indispensable for judging the impression of a space. Currently, illuminance and luminance are generally used photometric quantities in architectural space designing. Illuminance does not provide detailed information for all directions. Luminance can be measured for all directions but it must be independently measured for each location. Therefore, these two quantities are not sufficient to grasp the ambience of the entire space.

With the popularization and development of digital cameras, photometric methods using digital cameras have been proposed in recent years\(^{14,15}\). Digital camera is not yet commonly used as a measurement tool. While digital cameras can be purchased easily and at low price, model change is rapid. Digital cameras must be setup according to the characteristics of each model, but an outline for setup that accommodates all digital cameras and fish-eye lens is not yet established.

Aiming at understanding luminance distribution of the entire space, in this study, a luminance distribution measurement tool is prepared using NIKON FC-E8, fish-eye lens for equal distance projection, and NIKON COOLPIX995 (digital camera) with reference to previous studies\(^{14,15}\). The details and verification of this measurement tool have been previously reported\(^{16}\), so only an outline is indicated as follows.

Images taken by the digital camera with the fish-eye lens are read on the PC, and luminance
distribution is calculated using a computer program. All images are taken by manual mode and the iris is fixed at F4.7. Various shutter speeds are selected to match the brightness of the space. A total of six images, three different shutter speeds per upper and lower sites of the space, are photographed and luminance measurement range is set at 1-100000cd/m².

This is an effective method to probe the relationship between psychological and physical quantities of the space, since luminance for each location can be freely weighted by understanding detailed luminance distribution.

4. Basic review of the relationship between direction of light incidence and impression of brightness

Two experiments are conducted in order to understand the relationship between direction of light incidence and impression of brightness. To evaluate “impression of brightness of a space” which is the purpose of this study, experimental spaces large enough for the observer to be inside are prepared. The experiments are pursued with the observer inside the space.

First, in order to clarify the influence of visual direction on impression of brightness, the difference between impression of brightness is reviewed under two conditions: 1) the wall is the plane light source and 2) the ceiling is the plane light source. This experiment is conducted under two conditions: 1) with fixed visual direction (Experiment 1), and 2) with unfixed visual direction (Experiment 2). For Experiment 1, the target of visual direction is fixed to the desktop (Experiment 1-a) and to the observer’s front (Experiment 1-b). The influence of the relationship between visual direction and light incidence direction on impression of brightness is reviewed from Experiment 1. Further, the relationship between impression of brightness and horizontal and vertical plane illuminance is reviewed. For Experiment 2, observers are asked to state their impression of brightness under more natural conditions, namely by looking around the entire space.

Next, impression of brightness is reviewed under different arrangement patterns of the plane light source (Experiment 3). Particularly, difference in the impression of brightness is reviewed under two conditions 1) plane light source is concentrated and 2) plane light source is dispersed.

4.1 Effect of visual direction on impression of brightness
4.1.1 Experiment with fixed visual direction

(Experiment 1)

(1) Apparatus

Two experimental spaces of W:2000 x D:2000 x H:2000(mm) are prepared. The ceiling is the plane light source for Space A (direction of light incidence is vertical) and one of the walls is the plane light source for Space B (direction of light incidence is horizontal). Fluorescent lights are placed on a steel plate frame and covered with a reflecting sheet. By installing this lighting outside the space and letting lights permeate through a fabric sheet, which is the wall, a uniform plane light source is established.

(2) Experiment method

Scheffe’s paired comparison method 17) is applied. Thirty pairs made from a combination of six patterns of different directions of light incidence and light quantities are randomly presented to the observer as shown in Figure 3. Quantity of light is measured by the mean luminance of the entire surface area and brightness is set to three different levels that are of roughly even intervals on a logarithm axis.

<table>
<thead>
<tr>
<th>Levels of light quantity</th>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
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<tbody>
<tr>
<td>Space A</td>
<td>A-I</td>
<td>A-II</td>
<td>A-III</td>
</tr>
<tr>
<td>Mean luminance (cd/m²)</td>
<td>44</td>
<td>82</td>
<td>322</td>
</tr>
<tr>
<td>Space B</td>
<td>B-I</td>
<td>B-II</td>
<td>B-III</td>
</tr>
<tr>
<td>Mean luminance (cd/m²)</td>
<td>43</td>
<td>82</td>
<td>331</td>
</tr>
</tbody>
</table>

Figure 3 Light distribution of space for experiment 1

The observer is requested to sit in a chair (height 40 cm) for 15 seconds inside the first space. Then the observer is asked to shift to the next space, or to wait in the same space for 15 seconds (this 15 seconds is the length of the time required to shift to the next space in case the observer is asked to do so). The observer is then asked to verbally state his impression of brightness of the second space/condition against the first space/condition in seven steps: -3 (extremely dark), -2 (quite dark), -1 (somewhat dark), 0 (neither dark nor bright), +1 (somewhat bright), +2 (quite bright), and +3 (extremely bright). The observer is asked to wear an eye mask during the moving or waiting period so that his judgment will not be affected. Meanwhile, the duration of observation and the order in which spaces/conditions are presented were chosen based on preliminary experiments designed to confirm
that order effect, adaptation effect, or oppressive feeling do not occur.

For Experiment 1-a, a desk of W:750 x D:460 x H:750(mm) is placed at the center of the space. A plain white notebook is placed on the desktop and the visual direction is fixed on the notebook. For Experiment 1-b, the visual direction is fixed to the observer's front and not on the desktop. Subjects consist of five males and five females, all in their twenties.

3 Results and considerations

Figure 4 indicates the impression of brightness of Space A (where the plane light source is the ceiling) and of Space B (where the plane light source is the wall) by light quantity. In Experiment 1-a, the evaluation of brightness is higher when the plane light source is the ceiling for all light quantities and in Experiment 1-b, it is higher when the plane light source is the wall for all light quantities. These results show that evaluation of brightness becomes higher when the direction of light incidence is parallel to the visual direction and lower when vertical. From this fact, it can be concluded that direction of light incidence and visual direction have a significant impact on impression of brightness.

Figure 5 and Figure 6 show the relationship between brightness and both horizontal and vertical illuminance. The measuring point of both horizontal and vertical illuminance is set at the height of 1 (m) at the center of each space and measurement direction of vertical illuminance is the same as the visual direction in Experiment 1-b. In Experiment 1-a, the correlation between vertical illuminance and impression of brightness is low, but is high between horizontal illuminance and impression of brightness as represented by \( R \), the correlation coefficient between logarithm of horizontal illuminance and the impression of brightness, being 0.99. In Experiment 1-b, the opposite characteristic is observed, namely, the correlation between horizontal illuminance and impression of brightness is low, but is high between vertical illuminance and impression of brightness (\( R = 0.91 \)).

From the above results, it is reconfirmed that the impression of brightness of a space varies depending on the observer's visual direction. In other words, the observer's evaluation of brightness of a space does not become high by raising the brightness of a partial area on which visual direction is focused.

4.1.2 Experiment with unfixed visual direction

1 Experiment method

This experiment is conducted in the same spaces as Experiment 1. When wall is chosen for the plane light source, all four walls are used as plane light source and are of the same luminance, since the observer is requested to look around the entire space freely. However, since the area of the plane light source of ceiling differs from that of walls and the mean reflectance is not identical, quantity of light must be carefully monitored so that it is not affected by indirect light. In order to make the quantity of light identical, the mean luminance in both spaces are matched by adjusting the distance between the plane and the original light source. Similar to Experiment 1, with different direction of light incidence and three levels of light quantity, a total of six types of lighting are prepared as shown in Figure 7. Scheffe's paired comparison method is applied and the observer is requested to judge the impression of brightness of each space after freely looking around the entire space. Subjects consist of five males and five females, all in their twenties.
4.2 Influence of distribution of lights in terms of incidence angle on impression of brightness

Based on the result that evaluation of brightness is higher when light incidence is from the horizontal direction despite lowered luminance per plane when visual direction is not fixed, we will review the influence of the arrangement of plane light sources in the horizontal direction on the impression of brightness of a space.

(1) Experiment method

The apparatus for Experiments 1 and 2 are also used for this experiment. Five types of wall plane light source arrangements and three levels of light quantity are prepared as shown in Figure 10. Since this experiment aims at finding the effect of wall light variations, the ceiling and the floor are painted black. As in Experiment 2, light quantity is set to be consistent by making the mean luminance of the entire space uniform.

Evaluation method is the same as Experiment 1 and 2, and Scheffe's paired comparison method of seven levels from −3 to +3 is applied. Subjects are requested to cite their judgment verbally. Subjects consist of four males and four females, all in their twenties.

Five lighting patterns each with three light quantity levels (Set I: E-I, F-I, G-I, H-I, I-I; Set II: E-II, F-II, G-II, H-II, I-II; Set III: E-III, F-III, G-III, H-III, I-III) aimed at identifying the difference in impression of brightness depending on the arrangement of plane light source, and two patterns each with three light quantity levels (Set IV: E-I, E-II, E-III, I-I, I-II, I-III) aimed at understanding mutual relationship under varied light quantity levels are observed.

(2) Results and considerations of Experiment 3

As shown in Figure 11, a similar trend for all light quantity levels from Sets 1 to 3 is observed. Evaluation of brightness of a space increases as the
number of plane light sources increases from E to I. For F and G, which have the same number of plane light sources, F whose two plane light sources are facing each other has a higher brightness evaluation than G whose two plane light sources are adjacent to each other. As shown in Figure 12, brightness evaluation is higher for I than for E, and the difference in their evaluations becomes greater as light quantity increases. That is to say, the rate of increase in brightness evaluation caused by light quantity is higher in I than in E.

From the above results, increasing the number of plane light sources is more effective than raising the mean luminance per plane to obtain higher evaluation of brightness. Further, considering the relationship between F and G, evaluation of brightness is higher when plane light sources are dispersed than when they are localized in one section.

Meanwhile, if the visual field is limited to 180 degrees, according to past studies by Loe, the evaluation of brightness must be largely affected by the mean luminance of the visual direction and thus luminance of plane light source would significantly influence the impression of brightness. Hence the evaluation of brightness for E must be greater than F and that of H must be greater than I, if visual direction is fixed toward where the arrow points in Figure 13, due to their different mean luminance per plane. However, this relationship is reversed in our experiment, which adopts a 360-degree visual field observation. This indicates that the interpretation of “impression of brightness” is not identical in these two studies.

5. Application of luminance distribution measurement tool to impression of brightness

From the luminance distribution obtained using the luminance distribution measurement tool, physical quantities corresponding to impression of brightness of a space are reviewed. Images taken by fish-eye lens are distorted at the center and the photographed area per pixel varies. Prior to the review, this distortion aberration is compensated by the following formulae.

\[ D = \frac{(y' - y)}{y} \times 100 \]  

\[ D: \text{distortion aberration} \]  
\[ y: \text{ideal image height} \]  
\[ y': \text{actual image height} \]  

\[ y' = f\theta \]  

\[ y = f\tan\theta \]  

\( f: \text{focal distance} \)  
\( \theta: \text{angle of image (radian)} \)
The following formula is obtained by applying 5.2 and 5.3 to 5.1.

\[ D = ( \theta - \tan \theta ) / \tan \theta \times 100 \]  
\( D \): distortion aberration
\( \theta \): angle of image (radian)

Using the above formula, distortion of photographed area is compensated and the review of physical quantities is carried out.

5.1 Review of physical quantities relating to light quantity with consideration of visual direction

The result of Experiment 1 shows that impression of brightness may be largely affected and changed by quantity of light coming from one's visual direction. Quantity of light from the wall to which the observer's vision is frequently directed should be taken into account. Vertical illuminance is not an appropriate index when visual direction is not fixed since it is only regarding the light quantity projected on a fixed plane. Quantity that corresponds to impression of brightness of a space is sought under the precondition that the observer is to make one's judgment upon looking around the entire space.

5.1.1 Basic concept

One physical quantity of light from a spatial perspective is scalar illuminance. Scalar illuminance is a value obtained by simply integrating light quantities of all lights coming from all directions and is regarded as an unbiased and neutral index for indicating spatial light quantity. Based on illuminance value \( I \) of all directions obtained by the prepared measurement tool, \( E_0 \), a value equivalent to scalar illuminance, is derived by the following formula 5.5.

\[ E_0 = \int_0^\pi \int_0^{\pi/2} I(\theta_x, \theta_y) \cos \theta \, d\theta \, d\theta_y \]  
\( \theta_x \): horizontal angle \( \theta_y \): elevation angle

The following formula 5.6 is the definition of \( WE \) (Weighted \( E \)), which is a spatially weighted quantity of light corresponding to the impression of brightness.

\[ WE = \int_0^\pi \int_0^{\pi/2} I(\theta_x, \theta_y) \cos \theta \, d\theta \, d\theta_y \]  

Weight function \( w(\theta) \) is reviewed in the following section.

5.1.2 Review of weight function

In Experiment 2, where the visual direction is not fixed, the influence of light coming from horizontal direction on impression of brightness is significant. In other words, impression of brightness highly correlates with the value obtained by adding weight to quantity of light, such as to the vertical illuminance, which comes from the horizontal direction. Therefore, by applying Lambert's cosine law, \( WE \) is calculated by formula 5.7 which is to add weight to the light from the horizontal direction, or to define \( w(\theta) \) as \( w(\theta) = \cos \theta \). Meanwhile, this value \( WE \) is relatively consistent to cylindrical illuminance and named "physical quantity A" hereafter.

Physical quantity A unit

\[ = \int_0^\pi \int_0^{\pi/2} I(\theta_x, \theta_y) \cos \theta \, d\theta \, d\theta_y \]  

Figure 14 shows the relationship between physical quantity A and impression of brightness of the spaces in Experiment 2. While a high correlation of R=0.89 is evident, physical quantity A for C, when the ceiling is the plane light source, is generally lower than that for D, when walls are the plane light source. Further, slopes of their regression lines is not identical. These two facts indicate that influence of lights from the overhead is not properly taken into account.

Figure 15 indicates the relationship between mean luminance and impression of brightness of the spaces. As in Figure 14, the slopes of the regression lines for both plane light sources are not identical. The relationship between the plots for C and D is reversed when compared with Figure 14 where physical quantity A is applied. Again, this represents that the contribution of light from the overhead to impression of brightness is less, compared to that from walls in terms of light quantity and change in light quantity.

Upon reviewing the above results, when the observer is to look around the entire space before judging the impression of brightness, the weight added to the light of vertical direction is presumed to be 1 or less, since frequency of horizontal visual direction is higher than vertical visual direction. Yet at the same time, vertical visual direction must also be taken into account since observers may look in the upward direction occasionally. Therefore, the weight to be added to the light of vertical direction must be 1 or less but not 0. According to this concept, the weight \( (1 + \cos \theta / 2) \) is introduced (as elevation angle), and thus the weight for vertical direction is 0.5. Physical quantity B is defined by the following integral of horizontal light quantities by 360 degrees.
Physical quantity B unit

\[ R = \frac{1}{\sqrt{2}} \int \frac{L(\theta_x, \theta_y)}{\cos \theta_x} d\theta_x d\theta_y \]  \quad (5-8)

The relationship between physical quantity B and impression of brightness is shown in Figure 16. The correlation of R=0.95 is high, and the impression of brightness is similar regardless of the position of the plane light source.

The weight 0.5 for vertical direction may not be optimal, yet it was found that the effect of lights from the overhead must be taken into account. The significance of considering this effect can also be stated from the fact that the visual angle of human beings is said to be between upper 60 and lower 70 degrees and thus the observer is likely to look around the entire space if one is free to do so.

The above discussion provides the possibility of evaluating brightness with consideration of lights from all directions by introducing physical quantity B based on the idea of understanding frequency of observer's visual directions and integrating weighted light quantities according to direction.

![Figure 14 Relationship between A and Brightness of a space](image)

![Figure 15 Relationship between mean luminance and Brightness of a space](image)

5.2 Review of physical quantity with consideration of distribution of lights in terms of incidence angle

In the previous section, physical quantity B that attaches significant weight to lights from horizontal direction has been proposed as an example of physical quantity taking into account visual direction. This physical quantity does not include the influence of distribution of lights in terms of incidence angle. In Experiment 3, it is observed that impression of brightness varies according to the arrangement of plane light source of walls and that the evaluation of brightness is higher when plane light source is dispersed than when concentrated under equal total light quantities (mean luminance) in the space.

This fact suggests the necessity of considering distribution of lights in terms of incidence angle in addition to the influence of light quantity coming from one visual direction if evaluation of brightness is to be conducted under the precondition that the observer can look around the space freely. Below is our study regarding the effect of distribution of lights in terms of incidence angle on impression of brightness.

5.2.1 Proposal of directional diffusivity of light and smoothing by visual angle

In order to identify distribution of lights in terms of incidence angle, \( L_\theta(\theta_x) \), the integral by vertical direction for each horizontal angle, is calculated based on luminance distribution of the five spaces, E to I, used for Experiment 3. The value obtained by this calculation is normalized by its maximum value and the distribution is shown in Figure 17. Below is the formula.

\[ L_\theta(\theta_x) = \frac{1}{\sqrt{2}} \int L(\theta_x, \theta_y) \cos \theta_x d\theta_y \]  \quad (5-9)

where \( w(\theta_x) = 1 \), hereafter, expressed by \( \theta_x \)

where \( w(\theta_x) = \frac{1 + \cos \theta_x}{2} \), hereafter, expressed by \( b(\theta_x) \).
$L(\theta)$ is the value which expresses the brightness of a space without weighting and $b(\theta)$ is the value with weighting according to elevation angle. In Experiment 3, all spaces/sets are of the same condition for the direction toward the ceiling and thus, distribution of the two values is the same in a horizontal plane. In addition, in Figure 17, it can be clearly observed that the lights are arriving from a concentrated direction for E and G, both for which the judgment of impression of brightness is low.

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<thead>
<tr>
<th></th>
<th>Space E</th>
<th>Space F</th>
<th>Space G</th>
<th>Space H</th>
<th>Space I</th>
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<tbody>
<tr>
<td>$L(\theta)$</td>
<td>![Image of L(\theta)]</td>
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<td>$b(\theta)$</td>
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Figure 17 Spatial distribution of $L(\theta)$ and $b(\theta)$

Further, directional diffusivity of light, which is a physical quantity that takes into account distribution of lights in terms of incidence angle, is calculated from the above distribution. The relationship between this directional diffusivity and impression of brightness is studied. Directional diffusivity is the value, which indicates dispersion of lights in terms of horizontal incident angle and a single value per space is determined. As shown in Figure 18, this value becomes 0 when incoming light is from one direction and the maximum at 1 when light is radiating evenly from all directions. Directional diffusivity is obtained by the following formulae 5-10, 5-11, and 5-12.

If the number of directions are $N$, then the mean value of $L_n$, brightness of each horizontal direction, is

$$M = \frac{1}{N} \sum_{i=1}^{N} L_i \quad (5\cdot10)$$

The mean deviation from $M$ is

$$\Delta M = \frac{1}{N} \sum_{i=1}^{N} |L_i - M| \quad (5\cdot11)$$

Directional diffusivity $d$ is given by the following formula

$$d = 1 - \frac{m}{m_0} \quad (5\cdot12)$$

In 5-12, $m = \Delta M/M$, and $m_0$ is its value when incoming light is from a single direction.

Using the values in Figure 17, directional diffusivity of $L(\theta)$ and $b(\theta)$ is calculated and their relationship to impression of brightness is displayed in Figure 19. Values for both $L(\theta)$ and $b(\theta)$ are similar and the correlation is high for all light quantities. However, this indication in Figure 19 cannot express the difference of concentration and dispersion of lights when area of the plane light source is the same. This is evident from the fact that impression of brightness of F and G is different although directional diffusivity of $L(\theta)$ and $b(\theta)$ for F and G is the same.

![Figure 18 Basic concept of directional diffusivity](image)

![Figure 19 Relationship between brightness of a space and the directional diffusivity ($L(\theta)$, $b(\theta)$)](image)

The reason for such weakness in the indication is attributable to the mismatch between physical quantity and psychological quantity. In other words, $L(\theta)$ and $b(\theta)$ fluctuate drastically in accordance with horizontal visual direction change and the distribution does not correspond to psychological quantities. To resolve this, $sb(\theta)$ is introduced to smooth $b(\theta)$ by direction in the range of visual angle (horizontal angle 100 degree) so that the amount of light entering the human eye in a single sight is...
taken into account. The formula is as follows

\[ sb(\theta_n) = \sum_{n=0}^{N_n} \frac{b(\theta_n + n\phi)}{N_n} \]  

(5-13)

Distribution of \(sb(\theta_n)\) is indicated in Figure 20. Here, the change of \(sb(\theta_n)\) is smoothed for all spaces compared to the distribution in Figure 17, since \(sb(\theta_n)\) takes into account the light quantity within visual field rather than merely measuring physical brightness by direction.

![Figure 20 Spatial distribution of \(sb(\theta_n)\)](image)

Directional diffusivity for \(sb(\theta_n)\) is also calculated and its relationship with impression of brightness is presented in Figure 21. These figures successfully express the difference of F and G, which could not be achieved in Figure 19. Furthermore, the correlation coefficient is extremely high at \(R=0.99\). This shows the importance of the process of smoothing light quantity by visual angle with consideration of light quantity sensed in a single sight for understanding impression of brightness by light incidence angle.

![Figure 21-1 Relationship between directional diffusivity and Brightness of a space (I and II)](image)

![Figure 21-2 Relationship between directional diffusivity and Brightness of a space (III)](image)

Here, by introducing directional diffusivity, distribution of lights in terms of incident angle is expressed. Further, by folding in visual angle, continuity as well as variation of brightness in a space is more naturally described thereby enabling people's impression of brightness to be quantified.

6. The relationship of impression of brightness, light quantity, and directional diffusivity

"Light quantity \(WE\)" and "directional diffusivity of light" are proposed to meet the purpose of this study that is to identify physical quantities that correspond to impression of brightness of a space. Figure 22 is the relationship of impression of brightness, light quantity \(WE\), and directional diffusivity. Dots in the figure represent the spaces/conditions. This distribution is drawn by spline interpolation.

Impression of brightness rises when either light quantity or directional diffusivity becomes greater. Yet, the change in impression of brightness due to light quantity increase is less when directional diffusivity is low. From this characteristic, it can be predicted that in a space without a wall on one side, impression of brightness does not rise even when strong light is projected into the space.

This prediction is based on one perspective of the relationship in Figure 22. By comprehensively reviewing this relationship, comparison of spaces of different conditions or classification of various spaces may become possible in future.

![Figure 22 Relationship of module](image)
7. Conclusion
In this study, interpretation for “impression of brightness,” which was a vague concept in previous studies, is classified and the idea of “impression of brightness of a space” from a new perspective is proposed.

“Impression of brightness of a space” is reviewed by basic experiments with simplified model spaces. From the perspective that impression of brightness of a space is comprehensively judged from one’s memory obtained by looking around the entire space, we explained the mechanism of the observer’s judgment by introducing “quantity of light” and “directional diffusivity.” Accordingly, the possibility of quantitatively expressing “impression of brightness of a space” is confirmed.

Lighting must be comprehensively considered when designing a space. We believe that the indexes proposed in this study have the potential to become indexes for practical use by combining other elements.

In future, it is necessary to study the mutual relationship of various “impression of brightness” and review “impression of brightness of a space” under complicated luminance distribution that is more similar to an actual space. We are determined to advance our studies so as to prove the possibility of new methods that will replace former ones to express “impression of brightness of an entire space.”

References

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