STIMULUS DETERMINANTS OF BRIGHTNESS CONSTANCY AND THE PERCEPTION OF ILLUMINATION¹

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Simultaneous approaches to brightness constancy and to the perception of illumination were made in a Hsia-type experimental situation, where the immediate surround of standard disk was kept at a constant, very low luminance. 5 subjects were used. A log-log linear relation was found again between the standard luminance and the matched luminance. The obtained slopes ranged from 0.31 to 0.44. These are reversely related with the tendency toward constancy and mean a considerably strong tendency, which slightly decreased as the luminance ratio of the standard disk to the peripheral field increased. The data of illumination-matching showed that the matched illuminance increased almost proportionally to the standard illuminance. These results are inconsistent with a hypothesis of invariant reciprocal relation between the perceived illumination and the perceived brightness of a surface, and suggest that they have individual stimulus-correlates.

In photometry, the luminance (L), the stimulus intensity of the light reflected from a neutral surface toward the observer, is given by a product of the intensity of incident illumination, illuminance (E), times the reflectance (R) of the surface: $L=E \times R$. In psychology, the relative invariance of perceptual response to a surface of a constant reflectance with variation of illumination is called "brightness (lightness, whiteness, or color) constancy".

Historically, Helmholtz (1911, 1962) presented a view that we learn from our everyday experience to judge the color or brightness of bodies, eliminating differences of illumination on them, while Hering (1920, 1964) considered that contrast, adaptation, and pupillary adjustment might contribute to the stabilization of perceived brightness.

An early quantitative study on brightness constancy was conducted by Hsia (1943), who presented two gray disks in two

separately illuminated chambers and asked subjects to make brightness-matches between the disks under various conditions of illuminance and reflectance. In his study, the chambers were open at the rear and both disks were seen against a distant black background of a constant, very low luminance. This setup has a great advantage in reducing and equating brightness-contrast effect of the immediate surround on the disks. The role of contrast in the phenomenon of brightness constancy have been studied by many investigators (Leibowitz, Myers, & Chinetti, 1955; Leibowitz & Chinetti, 1957; Dunn & Leibowitz, 1961; Kozaki, 1963, 1965; Freeman, 1967).

The correlation between the judgements of illumination and of surface-brightness was originally suggested by Helmholtz, and has been restated in a more explicit form by Woodworth (1938). More recently, Beck (1959, 1961) studied this problem applying the matching technique on both judgements of illumination and of brightness of surfaces having various textures and backgrounds. His results suggested that these two kinds of judgements

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are not uniquely coupled, and have individual stimulus-correlates which are partially interrelated.

The experiments which will be reported below were conducted in 1959 for simultaneous approaches to brightness constancy and to the perception of illumination in a Hsia-type experimental situation. A part of this study was summarized in a mimeographed technical report (Oyama, 1962) and has been referred by Graham (1965). In spite of a long delay in publication and a technical problem in controlling illumination, the results of the experiment would still have some theoretical implications to such problems as the functional relationships between the stimulus variables and the matched luminance, the relation between brightness constancy and contrast, and the role of the perceived illumination in brightness constancy.

METHOD

Apparatus

Three wooden boxes of the same size were placed on a table before the subject in a dark room as shown in Fig. 1. They all were 38 cm in height, 27 cm in width and 50 cm in depth. A rectangular aperture, 12 cm wide by 6 cm

high, was cut from the front side of each box. The lower edge of the aperture was located 7 cm from the bottom of the box and the center of the aperture was about on the same level as the subject's eyes. Each aperture had a shutter which was controlled by the experimenter. The inside of each box was illuminated by a 40-watt glow lamp which was placed at the top and near the front of the box.

The middle of the three boxes was used as *Standard Box*. Its inside was covered by gray paper of 40% reflectance, except the back of the box which was left open. One of the five standard disks which will be described below was hung by a thin black string in the plane of the open back of box, and on the same level as the front aperture. A black velvet curtain was hung 180 cm behind the *Standard Box* and constituted the background of the standard disk.

A cardboard screen hung near the lamp cut off the light of lamp and kept it from reaching this velvet curtain. No other light source illuminated the curtain. Accordingly, the background of the standard disk was kept very dark black, independently of the illumination in the *Standard Box*. The background subtended visual angles of $40^{\circ}40'$ in height and $30^{\circ}20'$ in width, when the subject saw it through the aperture with his eyes close to the box.

The right box was located in the direction 40° to the *Standard Box* and served as *Comparison Box I*. Its inside was covered by two kinds of black paper. The reflectance of the paper covering the back wall was 3% and that of the paper covering the remaining parts was 8%. Against the black back wall at its center and on the same level as the front aperture, a rotating disk (Maxwell's top), whose white-black ratio was adjustable during rotation, was placed and used as the *comparison disk*. The white and black sectors were made from standard papers of Japan Color Research Institute. The reflectances were 88% and 5.5%, respectively. A metal head of screw was seen at the center of the disk. The diameters of the rotating disk and the screw head were 10 cm and 2 cm ($11^{\circ}20'$ and $2^{\circ}16'$ in visual angle), respectively.

The left box which was placed in the direc-

FIG. 1. A schematic representation of the apparatus used in this study.

tion 40° to the Standard Box was used as *Comparison Box II*. Its inside was covered by white paper whose reflectance was approximately 80%. At the center of the back of the box and on the same level as the front aperture, a 10 cm black disk (5.8% in reflectance) and a 3 cm × 3 cm white square (88%) were attached concentrically. They constituted the field of the minimum and maximum reflectances in this box, respectively, and were considered to serve as "cues" for judging the illumination.

Standard Disks

Five standard disks were used. Their diameter was 10 cm (11°20' in visual angle) and their reflectances were 5.8, 12, 24, 46, and 88% respectively. They were made from the standard gray papers of Japan Color Research Institute.

Illumination

As mentioned above, the inside of each box was illuminated by a 40-watt lamp. The power supply to the lamp was a 50-cycle, a.c. current. The voltage of the current supplied to the Standard Box was varied in five levels ranging from 53 v to 99 v by a variable voltage transformer (called Slidac in Japan and Variac in U.S.) and checked by a voltmeter. The voltage for the Comparison Box I was kept 100-v by the second set of transformer and voltmeter, and that for the Comparison Box II was adjustable by the third transformer placed below the box and near the subject seat.

The control of illumination through the voltage variation of power supply is accompanied by some variation of color temperature. However, Helson (1938) showed that the effect of light source of an unsaturated color on the perceived hue and brightness of illuminated surface were negligible. Consequently, the control of illuminance by means of voltage transformer was considered to be tolerable for the purpose of the present study, though it is of course not preferable. The illumination in the Standard Box was varied in five levels by this method. The illuminances at the bottom of the box directly below the lamp were 25, 50,

100, 200, and 400 lux (lumen/m²)², respectively. Those on the standard disks were 10, 20, 40, 80, and 160 lux.

The illuminance at the bottom directly below the lamp in the Comparison Box I and that on the comparison disk were 370 and 110 lux, respectively. The relation between the voltage and the illuminance in the Comparison Box II was measured for a wide range, and a calibration chart was made. When a 100-v current was supplied, the illuminances at the bottom and the "cue" disk were 660 and 360 lux, respectively.

Subjects

Five young women from 21 to 24 years old served as subjects. Some of them were college girls and others, office girls. They all had normal color vision and normal acuity although one of them wore glasses.

Procedure

All combinations between the five standard disks and the five levels of illumination in the Standard Box constituted 25 conditions.

Each subject served in two sessions. In each session, the subject was asked to make two brightness-matches and two illumination-matches for each of 25 conditions, in randomized order. Accordingly, each subject performed four brightness-matches and four illumination-matches in total.

After a buzzer rang, the shutters of the three boxes were opened. The subject was asked to observe Standard Box and Comparison Box I alternately and to adjust the white-black ratio of the comparison disk using a handle connected with it by a pulley system, until its brightness matched with the standard disk. After the subject finished two matches, she was asked to compare Standard Box and Comparison Box II, and to adjust the illumination of the latter to match subjectively with the former, using the knob of the transformer which was placed below the Comparison Box II and connected to a voltmeter behind the apparatus. When two illumination-matches were completed, the shut-

² One lux corresponds to 0.0929 foot-candle.

ters of three apertures were closed.

In both of the two kinds of matches, the experimenter alternately set the white-black ratio of the comparison disk, or the voltage supply to the Comparison Box II, too low and too high positions. The subject was allowed to observe the relevant boxes repeatedly to get satisfactory matches in brightness or in illumination. The adjusted angle of the white sector on the comparison disk and the adjusted voltage for Comparison Box II were recorded by the experimenter after each adjustment.

This procedure was repeated for the other 24 conditions. A five-minute rest-period was given after the 13th condition. One session took 25 to 50 minutes. The second session was a simple replication of the first session except that the order of conditions was reversed.

RESULTS

The adjustments of the angle of white sector of the comparison disk and those of the voltage for the illumination of Comparison Box II were averaged for each subject and transformed to the equivalent reflectance of the comparison disk and to the illuminance on the "cue" disk in Comparison Box II, respectively. The

FIG. 2. The reflectance of matched comparison disk as a function of the illuminance on the standard disk. Each line represents the data obtained with each standard disk, whose reflectance is shown near the line. Logarithmic scales are used for both axes.

equivalent reflectance = $(0.88 \times \text{white angle} + 0.058 \times \text{black angle})/360$. The calibration chart mentioned above was used for the transformation from voltage to illuminance.

Fig. 2 shows the mean equivalent reflectances of the comparison disks matched to the five standard disks under the five conditions of illumination. The abscissa represents the logarithmic illuminance, and the ordinate, the logarithmic matched reflectance. In such a graph, a line with a slope of unity represents a stage that the matched reflectance increases exactly in proportion to the illuminance on the standard disk (complete absence of brightness constancy), while a line of zero slope shows another state that the matched reflectance remains constant, irrespective of the illuminance (perfect constancy).

Five lines in Fig. 2 represent the results obtained with five standard disks of different reflectances. These straight lines are fitted to the data by the least square method. The slopes of these lines for the darkest to the brightest standard disks are 0.33, 0.32, 0.31, 0.40 and 0.44 respectively. These values of slope are smaller than those

FIG. 3. The reflectance of matched comparison disk as a function of the reflectance of standard disk. Each line represents the data obtained under each condition of illumination. This figure is another representation of the same data as Fig. 2. Logarithmic scales are used for both axes.

obtained by Hsia (1943), Leibowitz, Myers and Chinetti (1955), Leibowitz and Chinetti (1957), and Dunn and Leibowitz (1961). This fact indicates a stronger tendency toward brightness constancy in the present study as compared with the previous investigations. As Leibowitz (1956) and Oyama (1962) have already shown, one minus the slope value found in such a double log plot equals to the Thouless ratio which have been frequently used as an index of constancy. If we apply the Thouless ratio in these data, the values ranging from 0.56 to 0.67 will be obtained. These value indicate a considerably strong tendency toward constancy.

Fig. 3 shows the same data in a different way. The abscissa represents the logarithmic reflectance of the standard disk, while the ordinate shows the logarithmic reflectance of the matched comparison disk again. Five straight lines refer to the five conditions of illumination. They are fitted to the data by the least square method. Good linearity is observed also in this figure. Each line represents the matched reflectance to the standard disk of varying

reflectance under a constant illumination. If the matched reflectance is proportionally related with the reflectance of the standard disk, the line is expected to have a slope of unity, and if a complete constancy is realized, the plotted points should be placed on the broken line in the figure. The obtained slopes are 0.57, 0.68, 0.65, 0.66 and 0.73 for five conditions of illumination, in the order of increasing illuminance. These values indicate that the matched logarithmic reflectance increases more slowly than the logarithmic reflectance of the standard disk, even when the illuminations on the standard and comparison disks are kept constant.

Fig. 4 shows the logarithmic *luminance* of matched comparison disk as a function of the logarithmic *luminance* of the standard disk. This is the third representation of the same data. It is in a form comparable with Fig. 16.2 of Graham (1965, p. 458). Each line represents the data obtained under each reflectance condition of the standard disk, and is a parallel displacement of the corresponding line in Fig. 2. The luminance ratio of the standard disk

FIG. 4. The luminance of matched comparison disk as a function of the luminance of standard disk. Each line refers to each condition of luminance ratio of the standard disk to the brightest part in the peripheral field. Each ratio condition corresponds to each condition of the reflectance of standard disk. This figure is the third representation of the same data as in Figs. 2 and 3. Logarithmic scales are used for both axes.

to the brightest part of the peripheral field (the bottom) is shown with each line. Five lines are nearly parallel with each other. They are expected to converge into a line if the human eyes work in the same way as a photometer. But the obtained lines are not on a single line. This fact means that the luminance of the comparison disk matched to the standard disk of a constant luminance is varied when the luminance level of the peripheral field is varied. Fig. 4 indicates a tendency that a brighter peripheral field, which is caused by higher illumination, results in a lower matched luminance.

Fig. 5 shows the results of illumination-matching between Standard Box and Comparison Box II. The abscissa represents the logarithmic illuminance on the standard disk while the ordinate indicates that on the "cue" disk in the Comparison Box II. The broken line represents the objective matching of illumination between the standard disk and the "cue" disk. Each line refers to each condition of reflectance of the standard disk. The slopes obtained with the least square method are 1.02, 0.83, 1.00, 0.93 and 0.98, respectively. All the slopes are neary unity. This

FIG. 5. The results of illumination-matching. Matched illuminance as a function of the illuminance on the standard disk. Each line represents the data obtained with each standard disk, whose reflectance is shown in the figure. Logarithmic scales are used for both axes.

means that the matched illuminance increased proportionally to the standard illuminance. These lines are slightly higher than the broken line showing the objective matching, and their heights are slightly different from each other. In general, the brighter the standard disk is, the higher is the matched illuminance. It corresponds to our daily experience that illumination of the room having lighter walls is overestimated as compared with the room of darker walls.

DISCUSSION

A log-log linear relation between the illuminance on the standard disk (E_s) and the matched luminance (L_c), which corresponds to the product of the matched reflectance times a constant illuminance on the comparison disk, is indicated by Fig. 2. The same relation has already been shown by Hsia (1943), and expressed in a logarithmic function,

$$\log L_c = \log a + b \log E_s, \quad (1)$$

and in its transformation into a power function,

$$L_c = a E_s^b. \quad (2)$$

The values of slope (b) in the lines fitted to the data of the present study range from 0.31 to 0.44. They are much smaller than those found by Hsia, 0.52~1.02. This means that greater tendencies toward brightness constancy were found in the present study compared with Hsia's, because the slope is reversely related with the tendency toward constancy as shown by the relation: $\mathcal{Z}$ (Thouless Ratio) = $1 - b$.

Hsia (1943) indicated that the slope increased as the reflectance of the standard disk increased. Graham (1965), who re-analysed Hsia's data, restated practically the same tendency in terms of the luminance ratio of the standard disk to the peripheral field (walls and floor). This

tendency is found again in the present study: the obtained slopes are 0.33, 0.32, 0.31, 0.40, and 0.44, in the order of increasing reflectance. As suggested by Graham, the luminance ratio will have more theoretical meaning as a parameter than the absolute reflectance. But we have a practical difficulty in representing the peripheral luminance by a single value. Of course, the luminance ratio is exactly in proportion to the reflectance of the standard disk in the present study as in Hsia's, in both of which the peripheral field had a constant reflectance and was illuminated by the same light source as the standard disk.

The theoretically important findings common between the two studies are as follows: 1) the matched luminance increases as a power function of the illuminance, 2) the luminance ratio of the standard disk to the peripheral field is an important parameter in this kind of experiment as Graham has pointed out, and 3) the tendency toward brightness constancy decreases as the ratio increases. These tendencies have been confirmed in a wider range of illuminance variation by Leibowitz, Myers and Chinetti (1955), Leibowitz and Chinetti (1957), and Dunn and Chinetti (1961), who used the *immediate* surround illuminated by the same light source as the standard disk of a constant reflectance and varied the reflectance of the surround in three steps.

Another log-log linear relation exists between the reflectance of the standard disk presented under a constant illumination and the reflectance of the comparison disk matched to it, as shown in Fig. 3. This relation means that the logarithmic matched luminance is proportional to the logarithmic luminance of the standard disk which is presented with peripheral field of a constant level of luminance. The proportionality factors, the slopes of lines, were found to range from 0.57 to 0.73. These slopes represent the relative efficiencies of the standard to the comparison

luminance in raising the apparent brightness of respective disks. A slope less than unity indicates that increase in logarithmic luminance of the standard disk is less effective in raising brightness than the same increase in logarithmic luminance of the comparison disk, even when the luminance levels of both peripheral fields are invariant.

In his experiment on brightness constancy, Helson (1943) found that the luminance ratio of the comparison (highly illuminated) to the standard (shadowed) disk, which were matched in brightness with each other, decreased as the reflectance of the standard increased under a constant illumination, especially when the background of the two disks or that of the standard disk alone was black or gray. These results indicate a higher efficiency in raising brightness of the comparison disk than that of the standard, and are in close agreement with the tendency found in the analysis of Fig. 3. The difference in the peripheral luminance between the standard and comparison disks would be a factor producing the same tendency again in the present study.

Wallach (1948) presented a hypothesis that the brightness of achromatic color depends on the luminance ratio of the test region to its surround. If we could expand his hypothesis to the luminance ratio of the standard disk to the peripheral field, the perfect constancy (a constant matched luminance) would be expected in our first analysis shown in Fig. 2, and the direct proportionality (a slope of unity) would be expected in our second analysis shown in Fig. 3. Both expectations are not supported by the experimental results.

In the proximal stimulus pattern given to the eyes, the differences in illuminance and reflectance are converted into differences in luminances of the standard and comparison disks and in luminance distributions in the peripheral fields. All the variable and parameter in Fig. 4 are expressed in terms of luminance or lumi-

nance ratio, disregarding illuminance and reflectance. The plotted points in this figure do not constitute a single line. This means that the luminance of standard disk is not a unique factor determining the matched luminance, and that the luminance ratio, the parameter used in Fig. 4, is also a determinant of the matched luminance. The slopes of the lines shown in this figure are exactly the same as those of corresponding lines in Fig. 2, and they are positively related with the luminance ratio.

In their experiments on the effects of the luminance ratio of the test field to its immediate surround, the exposure duration, and the separation between the test and inducing fields, Leibowitz and his collaborators (1955, 1957, 1961) found that the tendency toward constancy generally increases in a situation where brightness contrast is expected to increase. From these findings, they concluded that contrast is a major factor contributing to the phenomenon of the brightness constancy, but some tendency toward constancy is still observable in the absence of contrast. More recently, Kozaki (1963, 1965) conducted some experimental analyses on the effects of the reflectance and size of the inducing and test fields, and interpreted her results as being inconsistent with the "contrast hypothesis" of brightness constancy (Freeman, 1967). For instance, some variation in reflectance of the inducing field produced a marked variation in level of the matched luminance (contrast), while the slope of the matched luminance as a function of illuminance (constancy) remained invariant.

In the present study, the immediate surround of the standard disk has a constant, very low luminance, and the separation between the standard disk and the nearest part of the peripheral field of higher luminance is $5^{\circ}20'$. The results of typical experiments on brightness contrast shows that the brighter field inhibits the dimmer field, while the dimmer field has little if

any effect on the brighter (Diamond, 1953; Heinemann, 1955), and that this inhibitory effect decreases as the separation between the two fields increases, reaching a very low level within a few degrees (Fry and Alpern, 1953; Leibowitz, Mote and Thurlow, 1953; Stevens and Diamond, 1965). Although these previous findings suggest a very small contrast effect in such a situation as the present study, a considerably strong tendency toward constancy is observed. In this point, the results of the present study are rather inconsistent with the "contrast hypothesis" of brightness constancy. However, the importance of the luminance ratio of the standard disk to the peripheral field repeatedly found in the analyses of the results indicates a close relationships of brightness constancy to brightness contrast in which the luminance ratio of the test field to its surround has been proved to be a very effective parameter. In consideration of this double-faced character of the present study, we can not conclude any simple relation between brightness constancy and brightness contrast.

As shown in Fig. 5, the matched illuminance increased nearly in proportion to the objective illuminance in the Standard Box. This fact suggests that the brightest part in the Standard Box, probably the bottom, played an important role in illumination matching, because the brightness of such part would have received little inhibitory effect from the remaining parts and the brightness would have increased nearly proportionally to the objective illuminance. The observed tendency that the level of the matched illuminance increased as the reflectance of the standard disk increased indicates that the luminance of the standard disk should also have been one of the stimulus factors determining the matched illuminance.

If an invariant reciprocal relation holds between the perceived illumination and the perceived brightness of a surface as Woodworth (1938) suggested, and if the matched

illuminance and the matched reflectance are reliable measures of the perceived illumination and the perceived surface-brightness, respectively, the matched reflectance is expected to be constant, irrespective of illumination (perfect constancy), when the matched illuminance is always in proportion to the objective illuminance. But this expectation is not supported by the results shown in Fig. 2. As Beck (1959, 1961) has already suggested, the perception of illumination and the perception of surface-brightness would have individual stimulus correlates and the impression of illumination may not be a necessary condition for brightness constancy, but a parallel phenomenon accompanying it. Neither the Helmholtz hypothesis of unconscious inference nor the Woodworth hypothesis of unconscious computation of albedo (on the basis of the intensity or luminance of reflected light and the registered illumination) could explain the results of the present study.

The analyses of the results suggested that the highest luminance in the Standard Box or some weighted average of luminances, which mostly depends on the highest luminance, is the most probable stimulus correlate of the perceived illumination, while both of the absolute luminance and the luminance ratio of the standard disk to the peripheral field are factors determining surface brightness.

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