Paper

The Influence of Lightness, Chroma and Hue of Chromatic Letters against an Achromatic Background on Readability and Equivalent Luminance Contrast

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ABSTRACT

The main purpose of coloring an object is to add information and to draw attention to it. However, the visibility of the visual object must not be spoiled by taking these effects too seriously. It is thought that explaining the influence of color on the visibility of an object is useful to show the effect of coloring except for the visibility after securing the visibility of a visual object. The final goal of this research is to show the establishment of visual environment design based on the visibility of chromatic object, and tries to explain the influence on the visibility of the color quantitatively. This paper shows the results of the subjective evaluation experiment. The experiment has various conditions systematized by color difference (lightness, chroma and hue under the CIELAB color system). The readability of chromatic documents was understood by focusing on the color difference as an index that shows the degree of influence of the color on visibility quantitatively. This paper shows the relationship between the color difference and the equivalent luminance contrast that is proposed by the authors to discuss the influence of the color easily.

KEYWORDS: readability, chromatic documents, luminance contrast, color difference, equivalent luminance contrast

1. Introduction

With the widespread use of PCs and color printers that enable the easy production of color images and documents, visual tasks involving chromatic pictures and letters have also become common in office environments. To date, many studies have been carried out mainly on "color appearance". In these studies, in order to cope with the effect of colors, various color systems have been proposed [for example 3)4)]. However, there are not enough studies that quantitatively analyze the effect of colored visual objects on visibility. The main purpose of adding color to an object is to enhance conspicuousness or to supplement information. Yet needless to say, an object's visibility must not be impaired by placing too much importance on such effects. The authors believe that the effects of colors can be maximized upon securing the visibility of the visual target, which is only achieved by clarifying the effect of colors on visibility.

The final goal of this study is to establish an environment design method based on visibility, which also takes into consideration the effect of colors. The effect of colors on visibility is quantitatively shown in this study.

Eastman, et al. [5)] measured visibility of a circular visual target at a visual angle of 10 minutes against a 2-degree visual angle background (both created by Munsell color chips) that are placed in a 10-degree white surrounding, using various combinations of colors of backgrounds and visual target. They showed the relationship between luminance contrast and visibility by hue, and proved that color contrast does not influence visibility when luminance contrast is 0.65 or above, while the influence is significant when luminance contrast is 0.4 or below. However, in their study, lightness difference is constant but chroma difference is not.

Ohshima [6)] indicated detectable distance of two color chips selected from eleven pure colors (the colors with highest hues in each color) and showed that detectable distance is longer when the energy difference between the two colors is larger, and the distance is not necessarily dependent on only lightness difference. However, in his study, either lightness difference or chroma difference are not constant.

Sakaguchi, et al. [7)] prepared a Landolt ring using colored sheets of paper and three types of lamps for illumination, and clarified 1) the relationship between hue difference and visibility by combinations of eleven colors with lightness ranging from 5 to 6.5 and chroma ranging from 6 to 9 (background is limited to 5G and N), 2) the relationship between lightness and visibility by

Part of the content of this paper were presented at 2002 annual conference of Kansai-Section Joint Convention of Institutes of Electrical Engineering JAPAN by Namba [1)] and Hara [2)].

combinations of achromatic colors, and 3) the relationship between chroma difference and visibility by a Landolt ring only whose chromas are dissimilar in a background of hue 5P, lightness 4.5, and chroma 4. They proved that lightness difference influences visibility the most. Visual acuity is more interrelated to chroma than hue when the background color is achromatic, and that visual acuity significantly deteriorates when the lightness difference is ±0.5 or less and chroma difference is 1–2 or less.

All of the above studies are targeting a detection threshold, and the data from these studies do not contribute to a visual environment design since the required visibility level in visual environment design is naturally higher than the threshold.

Hasegawa [8] conducted experiments where the visibility of text against a background, both created by using fifteen colors that were regulated by *xy*-chromaticity and their luminance contrast was set in 7–8 stages, was evaluated on a prepared scale. Inappropriate luminance contrast for each color combination is presented in his study.

Kubota, et al. [9] used the letters of six colors regulated by *xy*-chromaticity on a black background displayed on a CRT screen and made subjects conduct letter searching tasks after they adjusted the luminance of the letters to their best visibility levels. The study reviewed visual performance based on search time, error percentage, and subjective evaluations and proved that the visual performance differs depending on the color of the letters.

Funakawa [10] conducted experiments to calculate the critical area of color distinction against achromatic backgrounds by supplementing luminance noise to the stimulus so as to prevent luminance contrast from becoming the reason for detection. This made it possible to create multiple colors with the same color contrast against an achromatic color and of different hues. Subjects were asked to judge whether or not there was a target number in the eight numbers displayed in combinations of achromatic color and the colors of eight different hues under three different color contrasts against an achromatic color. As a result, the study proved that the larger the color contrast (chroma difference), the higher the readability. There is also a difference in readability depending on hues despite the color contrast being adjusted to become equal.

Hara, et al. [11] focused on color difference in a uniform color space and conducted experiments where subjects were to evaluate readability of several texts whose color difference against the background is identical under limited conditions, namely an achromatic background of luminance 65 cd/m^2 and luminance contrast 0.0 and 0.7. The luminance of letters of the texts is lower than that of background. The study proved that the effect of colors on readability differs even when CIELAB color difference is identical. Further, the study suggests that the effect of chroma and visual angle of the letters on readability can be dealt with independently by employing equivalent luminance contrast as an index to express the effect of color difference (lightness difference, chroma difference and hue difference).

None of the above studies provides sufficient data on the effect of colors on visibility in visual environment design since color conditions have not been systematically established. This is partly due to the difficulty of covering all of the attributes of colors for both letters and backgrounds and the difficulty in controlling colors. In addition, the relationship between the effect of other visual factors and colors is not yet clarified.

2. Visual environment design method based on visibility taking into account the effect of colors on visibility

It is well known that the primary factors that determine readability of achromatic documents are the three visual factors (size, contrast, and lightness). That is to say, the visual angle of letters, the luminance contrast (or the luminance difference), and the adapted luminance [12)-16)]. For chromatic documents, the effect of color contrast between letters and backgrounds on visibility must also be taken into account. In addition to the luminance contrast, also known as lightness difference, the color difference that reflects hue difference and chroma difference must be appended to the visual factors. The authors propose the luminance contrast that provides an achromatic document of the identical visual angle and under identical adaptation conditions with the same readability as that of the chromatic document as the equivalent luminance contrast of the target chromatic document[11]. Readability of a chromatic document can be obtained by regarding the equivalent luminance contrast of the chromatic document as the luminance contrast, which is one of the visual factors that determines the readability of an achromatic document [16]. The authors believe that the equivalent luminance contrast makes it possible to establish a visual environment design method based on readability of chromatic documents by applying the method of visual environment design based on the relationship between the aforementioned three visual factors of achromatic documents and their readability.

For establishment of a visual environment design method based on visibility incorporating the effect of colors, it is essential to conduct experiments in which the subjective evaluation of the visibility of an object is made under various stimulus conditions that are systematically established by arranging lightness difference, chroma difference, and hue difference. It is also essential to quantitatively clarify the relationship between color difference and the equivalent luminance contrast.

The aim of this study is to present the results of subjective evaluation experiments by which the readability of chromatic documents, under conditions that are systematically established by applying the color differences (lightness difference and chroma difference by each hue angle) in a CIELAB color space, is quantitatively expressed. It is also important to understand the relationship between the equivalent luminance contrast and two independent factors, lightness difference and chroma difference. In this study, color difference is produced by the lightness difference of each hue angle and each chroma difference, both independently since CIELAB color difference is proven not to correspond to the equivalent luminance contrast in our previous study [11].

Also in this paper, the achromatic background of luminance 65 cd/m^2 and chromatic letters with a lower luminance than their background are chosen from numerous color combinations. In order to easily display the systematically prepared colors, the visual target, for example the text, is presented on a luminous liquid crystal monitor placed in a dark surrounding. The color conditions are prepared by adding lightness differences and chroma differences to the conditions examined in our previous study [11], based on the knowledge of levels of various effects obtained by several past studies.

3. Outline of the subjective evaluation experiment

As shown in Fig. 1, a liquid crystal monitor (SONY TFT LCD color computer display SDM-N51AV, resolution 1024×768, RGB signal level can be adjusted in 256 steps for each pixel) is placed in a darkroom and covered by a black sheet of paper with a square opening of 20 cm×20 cm. In the center of the opening, the visual target, which is established by using various size letters and color combinations of letters and background, is

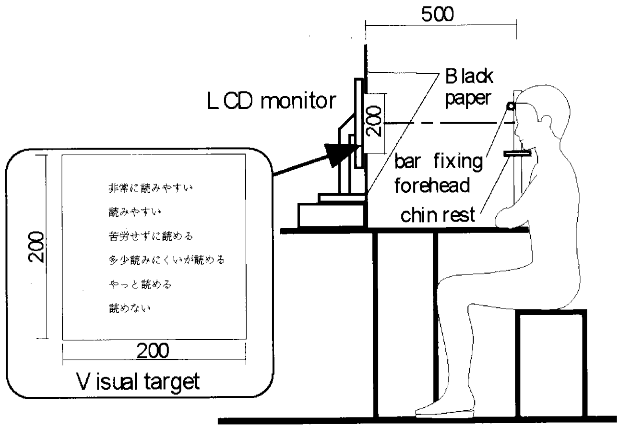


Figure 1 Experimental apparatus

presented in order. Subjects are requested to observe the visual target at a distance of 50 cm and to evaluate its readability. The entire visual field, except for the opening, is covered by the black paper or a black curtain. The visual target is a set of character lines in the Ming type font that express the six levels of evaluation from "unreadable" to "highly readable". The letters are prepared in three sizes, namely, 8, 14, and 25 points, or in a visual angle of 56.9', 31.9', and 18.2' by heights of the letters. There are three subjects (TS [age 23, male, visual acuity 0.8], YT [22, male, 0.8] and IN [24, male, 0.7].) Each subject is to conduct an evaluation five times per each condition.

The subject is adapted to a condition in which the background color is displayed in the entire opening for 10 minutes after one's entry to the dark room. The visual targets are presented in a random order that is dissimilar under each condition. The color of a visual target is replaced with another. In between the replacements, the background color is displayed in the entire opening for 3 seconds.

The background is an achromatic color which has the same chromaticity as a D65 light source of luminance 65 cd/m^2. Although the non-uniformity of the CIELAB color space is raised as an issue [for example 3] and it is known that the color difference is not equivalent in terms of visibility [11], these chromaticity coordinates are used in this study as a scale in order to systematically design color differences between the background and the letters. As to the targeted conditions of the chromatic letters, the combinations of seven luminance contrasts (0.0, 0.05, 0.1, 0.15, 0.3, 0.5, 0.7), five *ab* chroma differences (15.6, 25.6, 35.6, 45.6, 55.6) and six *ab* hue angles (30, 90, 150, 210, 270, 330[°]) are prepared as shown in Table 1. Meanwhile, in addition to the above settings, luminance contrasts of 0.2 and 0.9 are also prepared for the achromatic letters (*ab* chroma difference of 0). Hereafter, luminance contrasts, *ab* chroma differences, and *ab* hue angles shown in Table 1 are used to express the experimental conditions, or the reference values. The background is assumed to be a white Lambertian surface with a reflectance of 0.8 in order to specify the tristimulus values of luminous colors of the liquid crystal monitor in the CIE1931 colorimetric system, using chromaticity coordinates of a CIELAB color space to regulate the conditions of the experiments.

Lightness difference between the background and the letters becomes greater when the luminance contrast is higher. Luminance contrast is defined by the following formula. Luminances of the background and the letters are L_b and L_t, respectively.

$$C = \frac{L_b - L_t}{L_b} \quad \cdots\cdots (1)$$

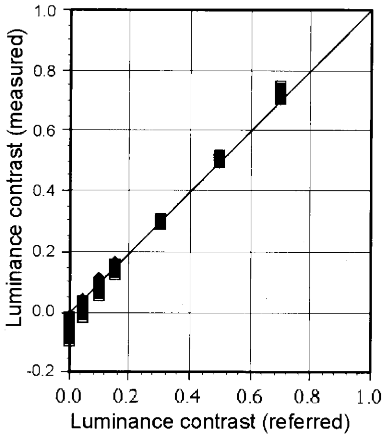


Figure 2 Referred value and measurement value of the Luminance Contrast

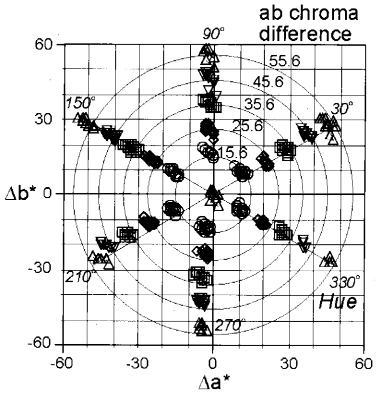


Figure 3 Color difference of the character color from the background color

Meanwhile, under the assumption that the background is a white Lambertian surface with a reflectance $\rho = 0.8$, the relationship of the luminance contrast C, CIE1976 lightness of both the background and the letters L_b^* and L_t^*, and lightness difference ΔL^* are expressed in the following formulae.

$$L_b^* = 116\rho^{\frac{1}{3}} - 16 \qquad L_t^* = 116\left(\rho(1-C)\right)^{\frac{1}{3}} - 16 \quad \cdots\cdots (2)$$

$$\Delta L^* = 116\rho^{\frac{1}{3}}\left(1-(1-C)^{\frac{1}{3}}\right) - 16 \quad \cdots\cdots (3)$$

Hence, the seven luminance contrasts of the chromatic letters correspond to lightness differences ΔL^* (0, 1.83, 3.72, 5.68, 12.1, 22.2, 35.6).

The color for the background or the letters to be displayed on the liquid crystal monitor is specified by adjusting the RGB signal level that is obtained by matching the tristimulus values of the CIE1931 colorimetric system measured by a colorimeter (TOPCON BM5A) at the center of the opening while displaying the color on the entire monitor with the tristimulus values of *XYZ* colorimetric system determined by the condition of the desired color. The identified RGB signal level is applied to each respective pixel to display the background and the letters.

Table 1 Colors of chromatic letters and settings excluded from the consideration

				Hue angle [°] 30	90	150	210	270	330
ab chroma difference	15.6	Luminance contrast	0	○	○	○	○	○	○
			0.05	○	○	○	○	○	○
			0.1	○	○	○	○	○	○
			0.15	○	○	○	○	○	○
			0.3	○	○	○	○	○	○
			0.5	○	○	○	○	○	○
			0.7	○	○	○	○	○	○
	25.6	Luminance contrast	0	○	○	○	○	○	○
			0.05	○	○	○	○	○	○
			0.1	○	○	○	○	○	○
			0.15	○	○	○	○	○	○
			0.3	○	○	○	○	○	○
			0.5	○	○	○	○	○	○
			0.7	○	○	○	○	○	○
	35.6	Luminance contrast	0	○	○	○	○	○	○
			0.05	○	○	○	○	○	○
			0.1	○	○	○	○	○	○
			0.15	○	○	○	○	○	○
			0.3	○	○	○	○	○	○
			0.5	○	○	○	○	○	○
			0.7	○	×	○	×	○	○
	45.6	Luminance contrast	0	○	○	○	○	○	○
			0.05	○	○	○	○	○	×
			0.1	○	○	○	○	○	○
			0.15	○	○	○	○	○	○
			0.3	○	○	○	○	○	○
			0.5	○	○	○	×	○	○
			0.7	○	×	○	×	○	○
	55.6	Luminance contrast	0	○	○	○	○	×	×
			0.05	○	○	○	○	○	×
			0.1	○	○	○	○	○	×
			0.15	○	○	○	○	○	×
			0.3	○	○	○	×	○	○
			0.5	○	×	○	×	○	○
			0.7	○	×	×	×	×	○

Each color is measured before and after the experiments by displaying the respective color on the entire monitor. Although each color had shifted slightly before and after the experiments, the relative color difference between the background and the letters was stable throughout the experiments since all colors had shifted in the same direction on the CIELAB color space (for example, the background chromaticity shifted 3.5 in terms of ΔE^*_{ab} from D_{65} as the standard). Fig. 2 shows the relationship between the reference value and the measured value of luminance contrast of chromatic documents. Although a dispersion of the measured values is observed in the lower luminance contrast, the measured luminance contrast is always high when the respective reference value is high and visa versa, under identical *ab* chroma difference and *ab* hue angle. The color difference between the background and the letters in the CIELAB colorimetric system is represented in Fig. 3 by symbols. Intersection points of concentric circles, that describe the desired *ab* chroma differences, and radiating lines, the *ab* hue angles, are the target chromaticity coordinates. Meanwhile, some conditions are extracted from Fig. 3 and from the later discussions since the measured values both before and after the experiments are largely dissimilar to the targeted value (such conditions are expressed by "X" in Table 1).

The gap between the targeted and practical chromaticity can be viewed as minimum, and thus the reference values are used in later discussions. In addition, the discussions are based on data obtained from the subject TS, since data from all of the three subjects have a similar trend.

4. The relationship between color difference of background and letters and readability

4.1 Luminance contrast (lightness difference) and readability

In Fig. 4, the relationship between luminance contrast (lightness difference) and readability of the document by visual angle of the letters for the chromatic documents of *ab* chroma difference 35.6 and *ab* hue angle 210° is shown. The area of each circle indicates the relative frequency of the readability, and the differences in the evaluations of the subject's multiple trials are from two to three steps on the readability scale. The symbols in the figure indicate 20, 50, and 80 percentile values. Each percentile value on the readability axis is calculated from cumulative relative frequencies of evaluations by each boundary or the highest end of the evaluation categories, similar to the method applied in our former study [11].

Readability increases as luminance contrast becomes greater. This trend can easily be understood by the relationship between luminance contrast and readability, which is represented by the percentile values.

Fig. 5 shows the relationship between luminance contrast and 50th percentile value of readability of the document by visual angle of the letters for the chromatic documents of *ab* hue angle 210° and representative *ab* chroma differences (15.6, 35.6, and 55.6). Readability increases as luminance contrast becomes greater for all *ab* chroma differences. Under the conditions that *ab* chroma difference is 15.6, the gaps between 50th percentile values for luminance contrasts 0.0 and 0.5 for the same visual angle letters are from three to four steps on the scale, whereas they are less than two steps under the conditions that *ab* chroma difference is 55.6. When *ab* chroma difference is large, readability is sufficiently high, even if luminance contrast is 0.0, owing to the color contrast, and thus the improvement effect of luminance contrast on readability is limited. Readability increases as the visual angle of the letters becomes wider for any combination of *ab* chroma difference and luminance contrast. A similar increasing trend of readability attributed to luminance contrast is observed in all hue angles, although the levels of readability improvement differ.

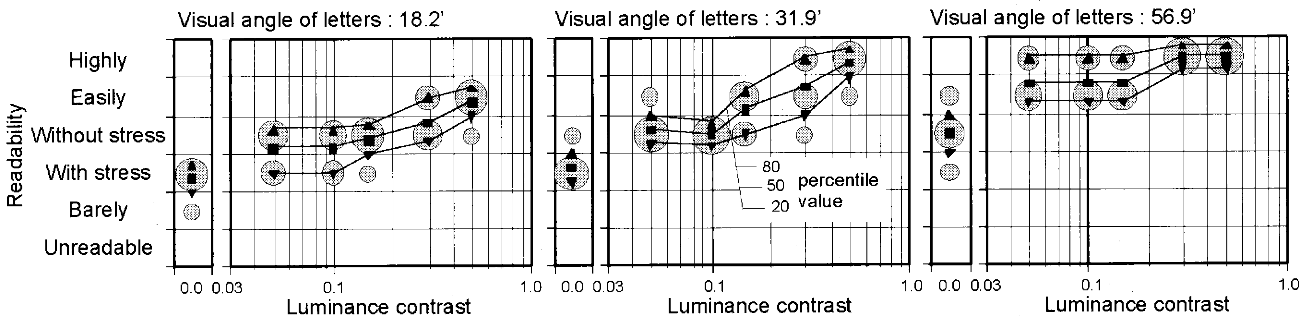


Figure 4 Relationship between luminance contrast and the readability of the chromatic document

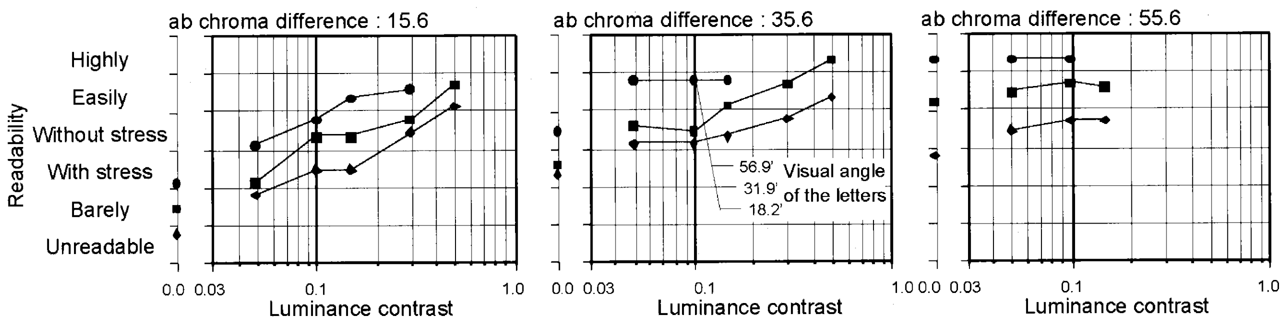


Figure 5 Relationship between luminance contrast and 50th percentile value of the readability of the chromatic document (Hue : 210°, Subject : TS)

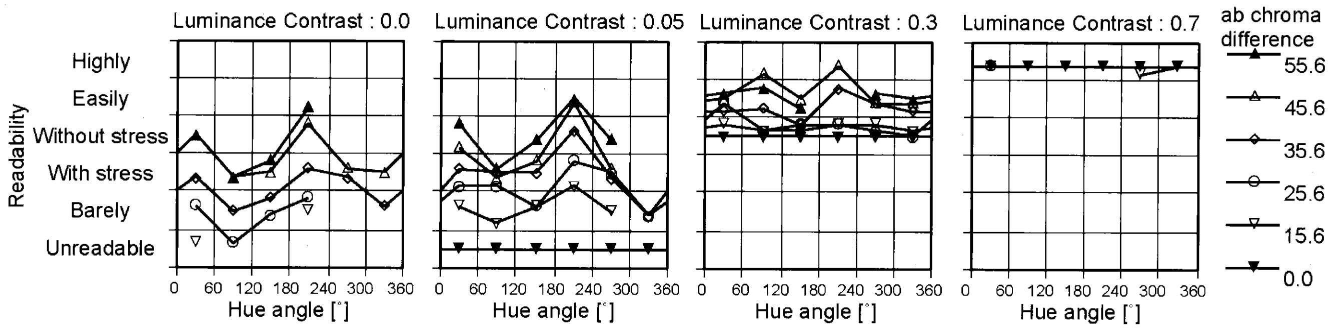


Figure 6 Relationship between hue angle and 50th percentile value of the readability of the chromatic document (Visual angle : 31.9', Subject : TS)

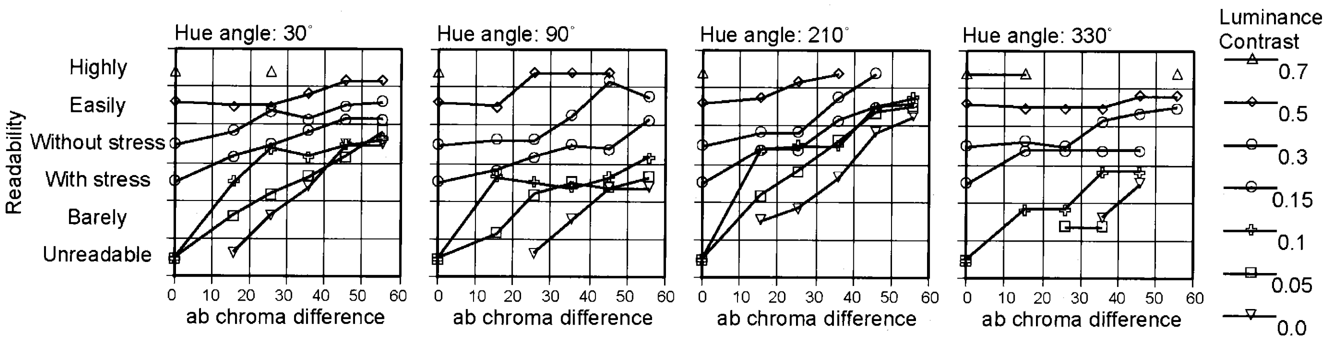


Figure 7 Relationship between *a*, *b* chroma and 50th percentile value of the readability of the chromatic document (Visual angle : 31.9', Subject : TS)

4.2 Hue angle and readability

Fig. 6 shows the relationship between hue angle and 50th percentile value of readability of the document by *ab* chroma difference for the chromatic documents of visual angle 31.9' and representative luminance contrasts 0.0, 0.05, 0.3, and 0.7. For the conditions that have luminance contrast 0.0, readability differs depending on *ab* hue angle, although the *ab* chroma difference is identical. Readability is high at *ab* hue angles of 210° and 30°, and low at 330° and 90°. Meanwhile, for the conditions where luminance contrast is 0.7, disparity in readability is hardly observed. The disparity in readability caused by hue angle becomes small as luminance contrast becomes greater.

4.3 Chroma difference and readability

Fig. 7 shows the relationship between *ab* chroma difference in the colors of background and letters and 50th percentile value of readability of the document by luminance contrast for the chromatic documents of visual angle 31.9' and *ab* hue angles 30°, 90°, 210°, and 330°. Readability rises as *ab* chroma difference increases at all levels of luminance contrast. For the conditions that have luminance contrast 0.05, the difference in readability for *ab* chroma 0 and 55.6 is four steps, but it is less than 1 when luminance contrast is 0.7. When luminance contrast is high, the readability of the document becomes sufficiently high even at *ab* chroma difference 0 (achromatic color), and the improvement effect of color contrast on readability is limited.

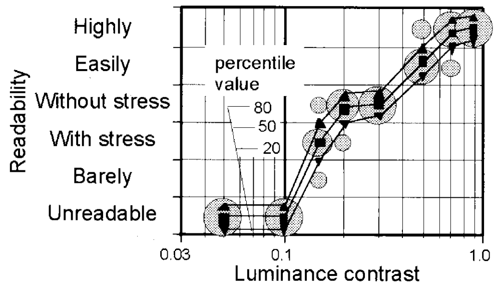
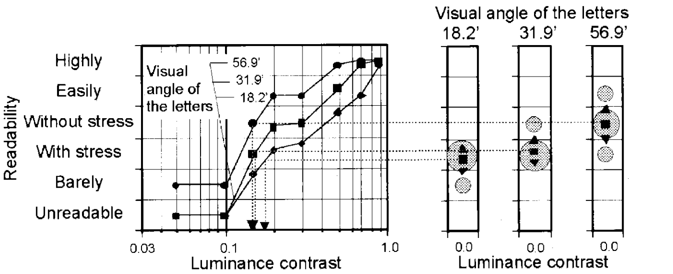


Figure 8 Relationship between luminance contrast and the readability of the achromatic document (Visual angle : 31.9', Subject : TS)

5. Calculation method for equivalent luminance contrast

Equivalent luminance contrast is defined as luminance contrast that provides equal readability, under an equal adaptation condition, to an achromatic document whose letters are of the equal visual angle to that of the chromatic document. The relationship between luminance contrast and readability of achromatic documents must be clarified in order to ascertain a calculation method to determine equivalent luminance contrast. Fig. 8 shows the relationship between luminance contrast and readability of achromatic documents whose letters are of visual angle 31.9'. The area of each circle indicates the relative frequency of evaluations, and each symbol indicates the percentile value for the respective readability. The differences in the evaluations of the subject's multiple trials are from two to three steps. Readability rises as luminance contrast becomes greater, and the distributions of the percentile values properly represent this trend.

Fig. 9 illustrates the calculation for equivalent luminance contrasts. Fig. 9 (a) shows the relationship between luminance contrast and readability in terms of 50th percentile value by visual angle of the letters. Readability increases as visual angle increases. Fig. 9 (b) shows the relative frequency and the percentile value of readability of the chromatic document of *ab* hue angle 210°, *ab* chroma difference 35.6, and luminance contrast 0.0 by visual angle of the letters. Each dashed line drawn from Fig. 9 (b) to (a) indicates the procedure of calculation for the respective equivalent luminance contrast. The equivalent luminance contrast is given by the luminance contrast that provides the same readability (equal 50th percentile value) to an achromatic document as that of the chromatic document. However, in case the percentile value for the readability of a chromatic document is out of the range of the respective percentile value for the achromatic document, the equivalent luminance value cannot be determined. Furthermore, if the percentile value for the readability of a chromatic document is the maximum or the minimum in the conceivable range, the equivalent luminance value is also indefinite.



a) Relationship between luminance contrastand 50 th percentile value of the readability of the achromatic document. (Subject : TS)

b) Relative frequency and percentile value of the readability of chromatic document. (Hue : 210°, Luminance contrast : 0.0,ab chroma :35.6, Subject : TS)

Figure 9 Calculating procedure of the equivalent luminance contrast

6. The relationship between color difference of background and letters and equivalent luminance contrast

6.1 Luminance contrast (lightness difference) and equivalent luminance contrast

Fig. 10 shows the relationship between luminance contrast and equivalent luminance contrast by visual angle of the letters for the chromatic documents of *ab* hue angle 210° and representative *ab* chroma differences (15.6, 35.6 and 55.6). Equivalent luminance contrast is higher when luminance contrast (lightness difference) is greater. The difference of the equivalent luminance contrasts by visual angle of the letters is small for the visual angles from 18.2' to 56.9'.

If readability of chromatic documents is affected only by luminance contrast regardless of their colors, then the equivalent luminance contrast would match the luminance contrast. Dashed lines in Fig. 10 are the sets where equivalent luminance contrast is equal to luminance contrast. It is observed that the equivalent luminance contrast is greater than the luminance contrast. This indicates that the readability of chromatic documents is the same as that of achromatic documents under higher luminance contrast. The color contrast must have enhanced readability. The difference between the logarithms of luminance contrast and equivalent luminance contrast is smaller when luminance contrast is greater. This difference is greater when *ab* chroma difference is larger. This indicates that if luminance contrast (lightness difference) is constant, the color combination of greater *ab* chroma difference has a larger effect on readability. For reference, the sums of the luminance contrasts and the equivalent luminance contrasts of luminance contrast 0.0 with identical hue angle and *ab* chroma difference are expressed by the dashed/dotted lines in Fig. 10.

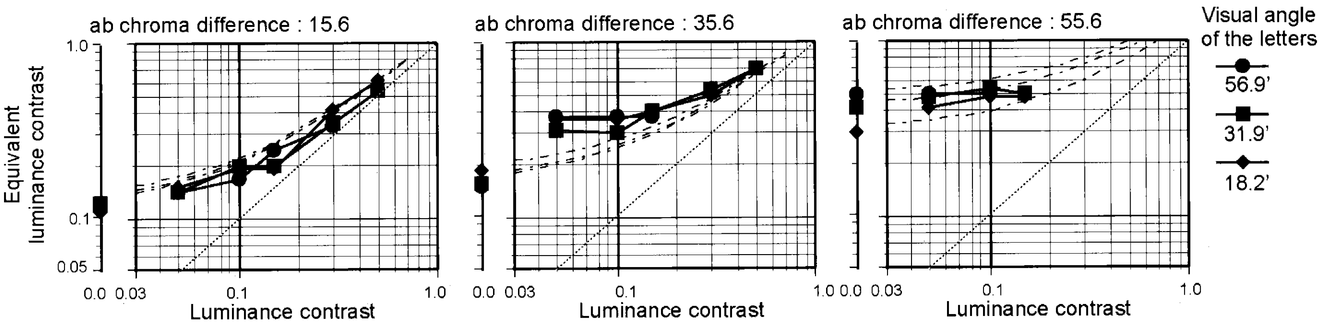


Figure 10 Relationship between luminance contrast and equivalent luminance contrast of the chromatic document (Hue angle : 210°, *ab* chroma : 35.6, Subject : TS)

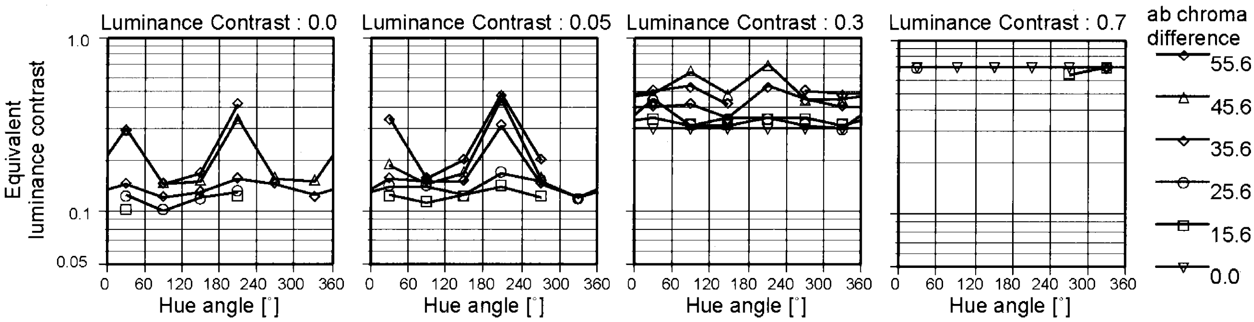


Figure 11 Relationship between hue angle and equivalent luminance contrast of the chromatic document (*ab* chroma : 35.6, Visual angle : 31.9', Subject : TS)

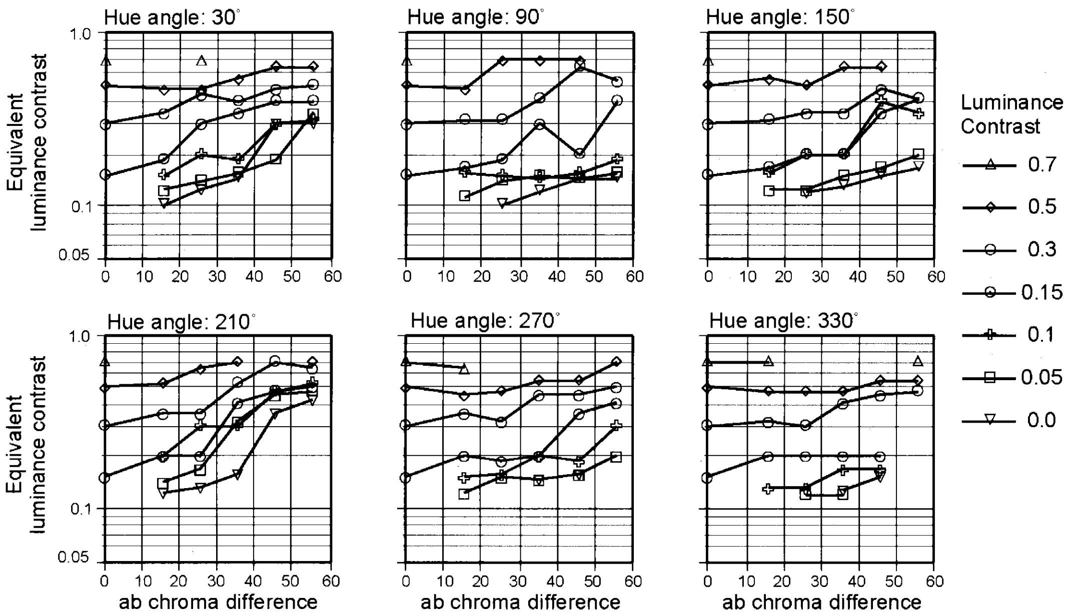


Figure 12 Relationship between hue angle and equivalent luminance contrast of the chromatic document (Visual angle : 31.9', Subject : TS)

6.2 *ab* hue angle and equivalent luminance contrast

Fig. 11 shows the relationship between *ab* hue angle and equivalent luminance contrast by each *ab* chroma difference for the chromatic documents of visual angle 31.9' and representative luminance contrasts 0.0, 0.05, 0.3, and 0.7. The equivalent luminance contrast differs depending on *ab* hue angle, and is high at *ab* hue angles 210° and 30°, while low at 330° and 90°, even under identical *ab* chroma difference. The CIELAB color difference of a document is equal to that of another, if their luminance contrasts (lightness differences) and *ab* chroma differences are both identical. However, the equivalent luminance contrast differs depending on hue angle when luminance contrast is 0.0 or 0.05. On the other hand, such difference is not observed when luminance contrast is 0.7. Equivalent luminance contrast becomes higher as *ab* chroma difference becomes larger, and the difference in equivalent luminance contrast by *ab* hue angle is greater when *ab* chroma difference is larger.

6.3 *ab* chroma difference and equivalent luminance contrast

Fig. 12 shows the relationship between *ab* chroma difference and equivalent luminance contrast by each luminance contrast and each *ab* hue angle for the chromatic documents of visual angle 31.9'. For all luminance contrasts, equivalent luminance contrast becomes higher as *ab* chroma difference becomes greater. The difference in equivalent luminance contrast created by *ab* chroma difference is large when luminance contrast (lightness difference) is low, whereas small when high. The level of such difference varies depending on hue angle. This trend is conspicuous when luminance contrast is low and *ab* chroma difference is large.

7. Difference in equivalent luminance contrast among subjects

Fig. 13 shows the relationship between luminance contrast and equivalent luminance contrast by subjects and *ab* chroma differences (15.6, 35.6, and 55.6) for the

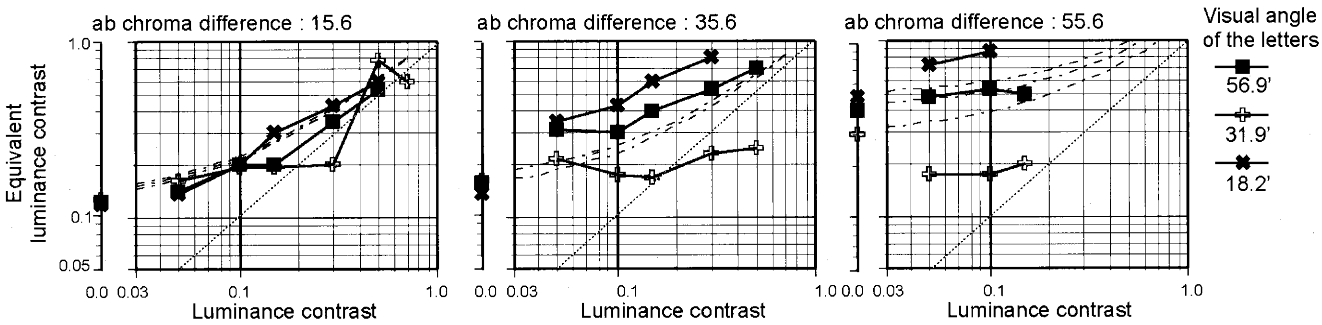


Figure 13 Relationship between luminance contrast and equivalent luminance contrast of the chromatic document for each subject (Hue angle : 210°, *ab* chroma : 35.6, Visual angle : 31.9')

chromatic documents of visual angle 31.9' and *ab* hue angle 210°. The difference in equivalent luminance contrast among subjects is greater at *ab* chroma difference 55.6 than that at 15.6. Such difference is greater when *ab* chroma difference is larger.

Although it is rare, some equivalent luminance contrasts are lower than the respective luminance contrasts, in other words readability deteriorates by color, as seen in the case of subject YT. For this subject, the difference in equivalent luminance contrast by *ab* chroma difference is smaller than that for other subjects. The document conditions selected for Fig. 13 are those in which the differences among subjects are most conspicuous. For most of the document conditions, the effects of lightness, chromaticity and hue on readability and equivalent luminance contrast are similar, although the levels of such effects slightly vary, to that observed for subject TS, whose results are indicated in Chapters 4 and 6.

8. Observation

Although the difference in 50th percentile values for readability of documents by visual angle is evident in Fig. 5, which indicates the relationship between luminance contrast and readability, the difference in equivalent luminance contrast by visual angles in a range from 18.2' to 56.9' is minimal in Fig. 10, which shows the relationship between luminance contrast and equivalent luminance contrast. A similar trend was observed for chromatic documents of the same visual angle range with luminance contrast 0.0 and *ab* chroma difference 35.6 in our previous study[11]. However, through this current study, it is further confirmed that the effects of color and visual angle on readability under broader conditions can be independently dealt with by the application of equivalent luminance contrast.

The equivalent luminance contrast (C_e) of a chromatic document with luminance contrast is similar to the sum of its luminance contrast and the equivalent luminance contrast (C_{e0}) of luminance contrast 0.0 with identical hue angle and *ab* chroma difference (dashed/dotted lines in Fig. 10). This suggests that the equivalent luminance contrast (C_e) of a chromatic document of the same color combination of any luminance contrast can be predicted by adding luminance contrast (C) and (C_{e0}), if the equivalent luminance contrast (C_{e0}) of luminance contrast 0.0 is obtained. (C_{e0}) represents the effect of the color. Yet, as understood from Fig. 8, or the relationship between luminance contrast and readability of achromatic documents, the effect on readability is limited if luminance contrast of the chromatic document is already high, since the effect of adding a constant value is minimal if the values initially differ significantly. In other words, as shown in Section 4.3, the color contrast effect on improving readability is smaller when the luminance contrast is greater. The equivalent luminance contrast and the predicted value obtained by the addition ($C_e=C+C_{e0}$) in Fig. 10 are close when considering the experimental conditions, namely, a) the evaluation of readability is made on a scale of six, b) the number of trials for evaluation is five, and c) the equivalent luminance contrast is calculated without smoothing the relationship between luminance contrast and readability (Fig. 9).

However, as shown in Fig. 13, the relationship between luminance contrast and equivalent luminance contrast varies depending on the subject and in some cases cannot be represented by such dashed/dotted lines in Fig. 10, although these cases are particularly different from the trend observed in most experimental conditions. It is judged that the results obtained from the three subjects alone are not sufficient to quantitatively express the relationship between color and equivalent luminance contrast. Further study, namely by subjective evaluation experiments involving more subjects, is necessary in order to quantitatively standardize this relationship.

The fact that readability and equivalent luminance contrast differ depending on *ab* hue angles despite CIELAB color difference being equal as shown in Fig. 6

and Fig. 11 adequately corresponds with the results obtained under the same conditions (luminance contrast of achromatic background 0.0 and *ab* chroma difference 35.6) presented in our previous study [11]. It is clarified that the difference in readability and equivalent luminance contrast gradually deteriorates as luminance contrast increases. In this study, the effect of *ab* hue angle on readability and equivalent luminance contrast under broader conditions is proven. In addition, it is found that the difference in equivalent luminance contrast by *ab* hue angle increases as *ab* chroma difference becomes greater, and that it decreases as *ab* chroma difference becomes smaller. Further study on such effects at various other hue angles must be carried out since it is found that the effect of *ab* chroma difference on equivalent luminance contrast differs depending on *ab* hue angles.

If the equivalent luminance contrast (C_e) of a chromatic document can be independently predicted from its luminance contrast (C) and the equivalent luminance contrast (C_{e0}) for the same color combination with the luminance contrast 0.0, this would be extremely convenient since it would indicate that the equivalent luminance contrast of a chromatic document with any luminance contrast can be derived from these two values (C and C_{e0}). The equivalent luminance contrast of a chromatic document on an achromatic background in any color combination can be calculated by merely expressing the relationship between *ab* chroma difference and equivalent luminance contrast by each *ab* hue angle for the chromatic documents that are of luminance contrast 0.0.

As discussed in Chapter 2, the level of readability of the chromatic document can be determined by regarding the equivalent luminance contrast of the chromatic document as the luminance contrast in terms of the relationship between the visual factors of achromatic document and their readability, and thus it is possible to design visual environments. In order to establish such a design method, it is necessary to conduct further studies, specifically, 1) to confirm the obtained relationships through gathering data from more subjects, and 2) display the relations between *ab* hue angle and *ab* chroma difference, and equivalent luminance contrast for chromatic documents of luminance contrast 0.0.

Throughout this study, the experimental results were presented without smoothing (regression) or standardization (i.e., averaging data of subjects), based on our understanding that the stage of study was not sufficient to describe the effects of colors on readability in a standardized manner. The authors believe that the knowledge obtained through this study will enable us to efficiently collect data from a greater number of subjects in a broader range and thus, to clarify the standardized relationship between color difference and equivalent luminance contrast.

9. Notes

The effect of colors on visibility in this study is based on the results obtained from the chromatic documents displayed on a liquid crystal monitor placed in a dark surrounding. This experimental condition considerably differs from ordinary observation conditions. It is necessary to clarify the extent to which the obtained results can be applied and to study the effect of colors on visibility under ordinary observation conditions.

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References

(1) I. Namba, Naoya Hara, Tarow Noguchi : Study on readability of chromatic document Part 2 — Relationship between visual factors of chromatic document with achromatic background and readability —, Record of the 2002 Kansai-Section Joint Convention of Institutes of Electrical Engineering JAPAN, p.G300 (2002).

(2) Study on readability of chromatic document Part 2 — Relationship between visual factors of chromatic document with achromatic background and equivalent luminance contrast —, Record of the 2002 Kansai-Section Joint Convention of Institutes of Electrical Engineering, JAPAN, p.G301 (2002).

(3) Chapter 4 Color system : Handbook of Color Science [second edition], color associ. of Jpn.: University of Tokyo press, pp.87-129 (1998).

(4) Chapter 5 Color order system : Handbook of Color Science [second edition], color associ. of Jpn.: University of Tokyo press, pp.131-175 (1998).

(5) A.A. Eastman: Color Contrast vs Luminance Contrast, Illum. Engng., 63-12, pp.613-620 (1968).

(6) M. Ohshima: Environment physiology, Ishiyaku publishers, Inc., pp.51-54 (1967).

(7) T. Sakaguchi, and T. Noguchi: The Effects of Hue, Value, and Chroma on the Visibility, J. Illum. Engng. Jpn., 53-5, pp.213-218 (1969).

(8) T. Hasegawa: Readability asessment on low luminous contrast teletexts, J. Color Sci. Assoc. Jpn., 11-3, pp.146-151 (1987).

(9) S. Kubota, M. Ohkura, M. Takahashi, H. Iida, and A. Nishioka: Visual Performance as a function of colors of characters on a CRT Display, The Journal

of Science of Labour, 60-8, pp.357-363 (1984).
(10) M. Funakawa: Psychophysical Experiments on the Legibility and Chromatic Contrast, J. Illum. Engng. Jpn., 84-11, pp.799-808 (2000).
(11) N. Hara, I. Namba, and T. Noguchi: Equivalent Luminance Contrast Representing the Relationship between Color Difference and Readability of Chromatic Documents, J. Light & Vis. Env., 27-3, pp.165-171 (2003).
(12) S. Kawai, and R. Krossawa: An Empirical Fomula for the Relation of Readability to Illuminance, J. Illum. Engng. Jpn., 57-6, pp.580-583 (1973).
(13) Y. Nakane: Study on the visibility and the appropriate illuminance of the printed letters, Trans. Architec. Inst. Jpn., 229, pp.111-120 (1975).
(14) R. Satoh, K. Itoh, and H. Ohno: Lighting Design Method Based on Visual Ease Evaluation— Usefulness of the Visual Ease Level (VEL) as a Evaluation Index of Lighting —, J. Illum. Engng. Jpn., 64-10, pp.541-548 (1980).
(15) Y. Nakane: Lighting Design Method Based on Readability Evaluation, J. Illum. Engng. Jpn., 65-10, pp. 534-540 (1981).
(16) N. Hara, and R. Satoh: "Equi-Readability Surface" of three visual factors corresponding to various design level about readability of documents, J. Architec. Env. Engng., 575, pp.15-20 (2004).