Color Universal Design without Restricting Colors and Their Combinations Using Lightness Contrast Dithering

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Abstract: This paper proposes a new color universal design method without restricting usage of colors and their combinations using dithering technique. A key idea is that a solid color and a dithering of darker and lighter colors which approximate the solid color may look almost similar for people with normal color vision, while they could be distinguishable for people with color vision deficiencies since one is solid and the other is a pattern of dark and light colors. Efficacy of this method has been confirmed through some experiments.

Keywords: universal design, color vision deficiency, lightness contrast dithering.

1. Introduction

Colors are important in design in terms of both expressionism (e.g., express beauty) and functionalism (e.g., transmit information). Recently, color universal design, which is the way of color design enabling all the people to understand the information regardless of their color visions has become more and more important [1]. Typical method of color universal design is to use only colors and their combinations which are perceivable and distinguishable for people with color vision deficiency [2][3] (Figure 1). Such restriction of color usage, however, may lead to unavailability of some color conventions or limitation of color aestheticity. To solve these problems, the authors propose a new color universal design method of using dithering technique which strikes good balance between less restrictions on available colors and their combinations and color perceivability and distinguishability for people with color vision deficiency.

2. Basic Concept: Dithering for Color Approximation and Color Distinction

Dithering is a technique used in computer graphics to express the intermediate color with a limited color palette. In our research, a solid color is approximated by dithering of its darker (L-ΔL) and lighter (L+ΔL) colors, where L is a parameter for color lightness (Figures 1 and 2). The authors conceived this idea partly from the knowledge that people with color vision deficiency are more sensitive to the difference of lightness of colors than people with normal color vision [4]. Suppose there is a color design (C in Figure 3) using two solid colors which cannot be distinguished by people with color vision deficiency (C'). Here the authors built a hypothesis as shown in Figure 4 that if one solid color is approximated by a lightness contrast dithering of its darker and lighter colors, the resulting color design C_d may look similar to C by normal color vision whereas C_d' could be more distinguishable by people with color vision deficiency than C' since one color is solid and the other is a pattern of dark and light colors. The lightness contrast dithering method has such parameters as the size of dithering, lightness $\pm\Delta L$ and dithering pattern (e.g., checkered, dots, stripes).

The purpose of the research is to confirm the availability of the proposed color universal design by lightness contrast dithering method and analyze and clarify the conditions on colors and dithering parameters to obtain appropriate visual performance. Although the lightness contrast dithering method can be applied to both print and display, the authors first focused on the print and dithering with checkered or stripe pattern.

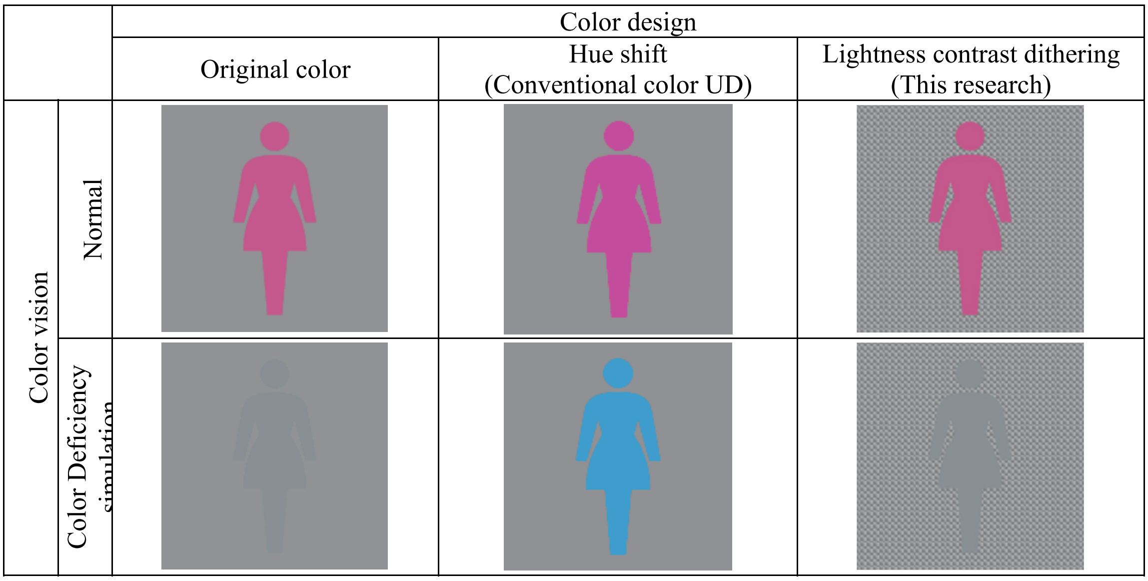

Figure.1 Way of Color Universal Design

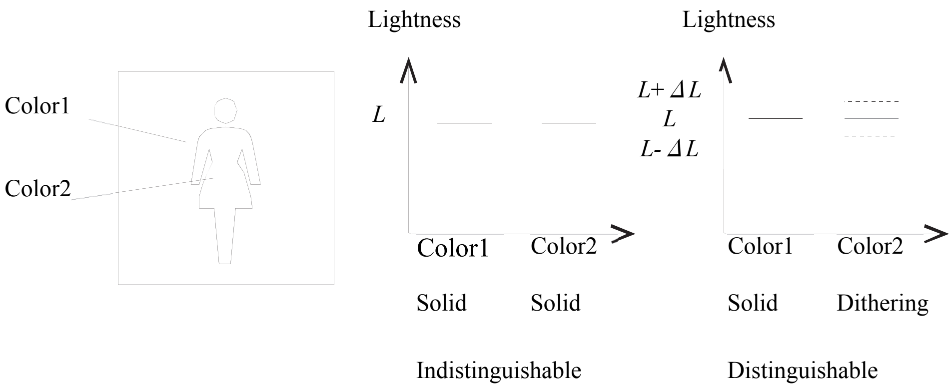

Figure 2. Color Distinction by Dithering

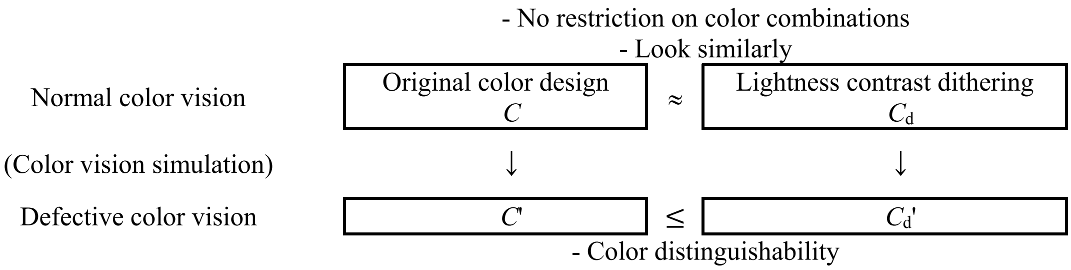

Figure 3. Expected Effect of Dithering Method

3. Relationship between Lightness Contrast Dithering Parameters and Distinguishability

3.1 Purpose

In preceding research, we focused on dithering of a check pattern and revealed what combinations of lightness contrast and dithering size guarantee distinguishability [5]. In this research, we examine stripe patterns, i.e., vertical stripe, horizontal stripe, and oblique stripe, and try to elucidate relationships between lightness contrast dithering parameters including stripe orientation and distinguishability of printer figures.

3.2. Method

We had three steps; making samples, arranging circumstances, and conducting the experiment.

First, we decided what parameters we use. We selected each three levels for lightness contrast ΔL in L*a*b* color space and dithering size.

Lightness contrast ΔL: 1, 4, 7

Dithering size (mm) :0.3, 0.4, 0.5

Besides, to compare with proceeding research, we also used checker pattern. Concerned about check, the parameters were chosen following way.

Lightness contrast ΔL: 1, 5, 9

Dithering size(mm) : 0.4, 0.7, 1.0

These levels are selected for following three reasons. 1.More than about 0.3mm (0.4mm for check) dithering size can be printed clearly with the printer. 2.Our program which generates dithered patterns can make every 0.1mm size of dithering. 3.In our preliminary subjects could consider stripe dithering whose lightness contrast is 7, and dithering size is 0.5mm as an average color (9 and 1.0mm for check).

Second, we chose pink and gray which are indistinguishable by deuteranopes who have no (or less) M cones which response to light of middle wavelength.

As print samples, we selected the following thirty-six alphanumeric and simple Japanese characters each of which seems comparatively non-confusable to others. (Figure 4)

A	a	d	E	G	g	K	m	R
W	y	3	4	5	6	8	9	え
か	す	せ	そ	と	の	ふ	ま	み
ゆ	よ	る	四	五	六	七	九	十

Figure 4. Sample Letters

If these letters are used as they are, it may be possible that subjects guess the letter though they recognize only some portion of the letter. Therefore, we apply some deformation to the letters as shown in Figures 5,6, which is a letter ‘g’.

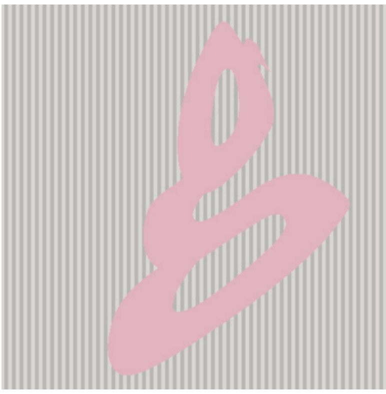

Figure 5. Vertical Dithering (Normal)

Figure 6. Vertical Dithering (Color Deficiency)

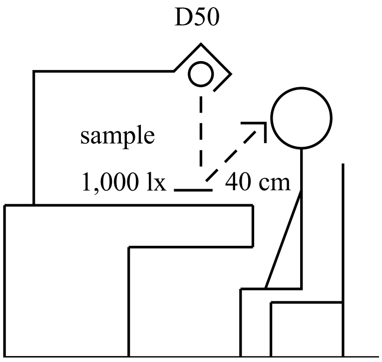

Figure 7. Scheme

At this point, there is a problem that complexity of the letter shape may have effect on distinguishability, so we quantified the complexity with following definition [6].

$Co = P^2/A$ (*Co*: complexity; *P*: perimeter; *A*: area)

We measured the perimeters and the areas of the letters by counting their pixels. Depending on this data, we arranged the order of the samples so that the effect of complexity can cancel each other. Finally, we used simulated colors generated with UDing[7], a color vision simulation software. Therefore, we can simulate subjects with color vision deficiency. One of the simulated samples, which are printed with an inkjet plotter PX-H10000 (EPSON) and photo paper (KA450PSKR , EPSON)is shown in Figure 5.

The second step is to arrange circumstances, whose schema is shown in Figure 7. Lighting is based on D50 which is a regular lighting for experiment on color in JIS Z 8726 (Japanese Industrial Standards), and illuminance is 1,000 lx. Subjects are ten males with normal color vision in their twenties.

Then, we had the subjects seated on a chair, and put their heads onto a pedestal so that the distance between their eyes and the samples can be sustained 40 cm. Then, we had them close their eyes and set one of the samples. When allowed, they can begin to answer. The answer is two ways; one is to just answer the letter and the other is to say he or she cannot recognize. The answers are quantified into 1 (which means the answer was correct) and 0 (which means the answer was incorrect or they cannot recognize) in order to analyze statistically.

3.3 Analysis and Result

We analyzed the data with ANOVA and discriminant analysis.

The responsive variable is how many subjects could answer and the explanatory variables are the lightness contrast, the dithering size of the stripe and the pattern of dithering.

Table 1. Result of ANOVA

Factor	Type III sum of squares	degrees of freedom	mean square	F Value	P Value	Judgment
Pattern	9.0000	3	3.0000	8.3077	0.0029	**
Lightness Contrast	96.0556	2	48.0278	133.0000	0.0000	**
Dithering size	37.3889	2	18.6944	51.7692	0.0000	**
Pattern*Contrast	9.5000	6	1.5833	4.3846	0.0142	*
Pattern*Dithering size	6.1667	6	1.0278	2.8462	0.0581	
Contrast*Dithering size	52.7778	4	13.1944	36.5385	0.0000	**
Pattern*Contrast*Dithering size	0.0000	0	-			
Error	4.3333	12	0.3611			
Total	215.2222	35				

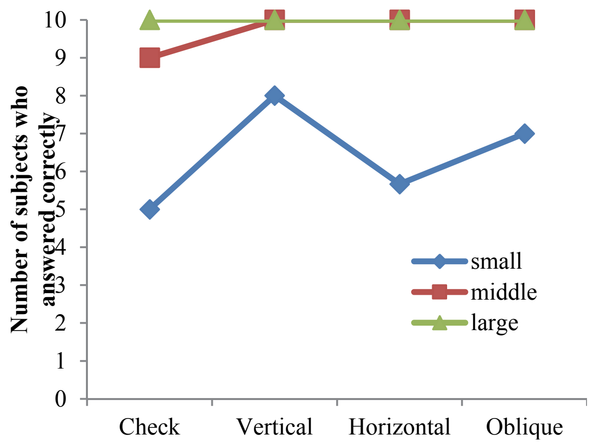

Figure 9. Average of Each Level (Pattern * Contrast)

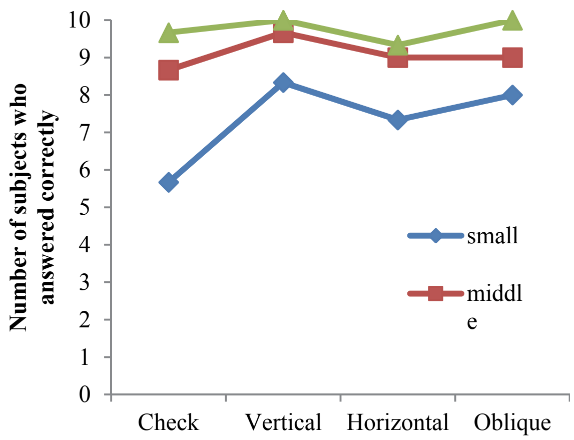

Figure 10. Average of Each Level (Pattern * Size)

Table 1. Result of Multiple Comparison Method (Small Contrast) (Pattern * Lightness Contrast)

Level1	Level2	Average1	Average2	Error	Standard Error	Statistic	P Value	Judgment
Check	Vertical	5.0	8.0	3.0	0.49	6.1	0.0003	**
Check	Oblique	5.0	7.0	2.0	0.49	4.1	0.0072	**
Horizontal	Vertical	8.0	5.7	2.3	0.49	4.8	0.0023	**

Table 2. Result of Multiple Comparison Method (Small Size) (Pattern * Dithering size)

Level1	Level2	Average1	Average2	Error	Standard Error	Statistic	P Value	Judgment
Check	Vertical	5.7	8.3	2.7	0.49	5.4	0.0008	**
Check	Horizontal	5.7	7.3	1.7	0.49	3.4	0.024	*
Check	Oblique	5.7	8.0	2.3	0.49	4.8	0.0023	**

The judgment on Pattern shown in Table1 means pattern is significant, so pattern has effect on distinguishability. Besides, Figures 9 and 10 indicate that vertical stripe was read by more subjects than other patterns were. Moreover, Tables 2 and 3 indicate vertical looks most distinguishable. Depending on these facts, we built up a hypothesis that vertical stripe is superior in the point of distinguishability.

In order to reveal what parameters have distinguishability, discriminant analysis was conducted; the responsive variable is whether the subjects could answer or not and the explanatory variables are the lightness contrast, the dithering size of the stripe, and complexity of the letter. Table 4 shows the result of the analysis on vertical stripe. There is a problem, which is *Co* is significant only in vertical stripe data. It means that complexity does not explain the effect of the shape of letters on distinguishability well.

Table 3. Judgment on Each Parameter (Vertical)

Variable	Wilks' λ	F value	Degrees of freedom 1	Degrees of freedom 2	P value	Judgment
Lightness Contrast	0.8771	11.7710	1	84	0.0009	**
Dithering Size	0.9139	7.9136	1	84	0.0061	**
Complexity	0.9497	4.4448	1	84	0.0380	*

Then we eliminated the factor of Co, and analyzed the data again. The result is shown below.

Z: Discriminant Function, L: Lightness Contrast, s: Size (mm) (Seen from 40cm far.)

Vertical $Z = 0.34L + 8.6s - 4.8$

Horizontal $Z = 0.44L + 6.1s - 4.2$

Oblique $Z = 0.39L + 7.7s - 4.6$

Regardless of the Pattern, distinguishable parameters adopted in this experiment were the same. They are plotted in Figure11.

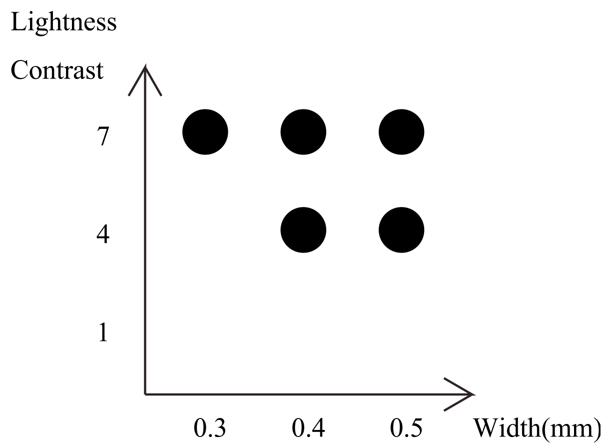

Figure 11. Distinguishable Parameters (Vertical, Horizontal, Oblique)

To estimate accuracy of discriminant function, two factors are said to be useful, which are correlation ratio and hit ratio. The result showed that all of the discriminant functions are proper. Moreover, look at the prospect x data matrix in Tables 5, 6, 7.

Table 4. Hit Ratio (Vertical)

		Prediction		Hit Ratio
		1	0	
Data	0	0	6	100.00%
	1	60	24	71.43%
Total				73.33%

Table 6. Hit Ratio (Oblique)

		Prediction		Hit Ratio
		0	1	
Data	0	13	0	100.00%
	1	17	60	77.92%
Total				81.11%

Table 7. Hit Ratio (Vertical)

		Prediction		Hit Ratio
		0	1	
Data	0	9	0	100.00%
	1	21	60	74.07%
Total				76.67%

Though the accuracy is only 70% to 80%, what are expected to be distinguishable are always actually distinguishable. Thus, we concluded that when the discriminant function is positive, the combinations can be said to be safe for distinguishing.

3.4. Section Conclusions

It is true that the number of participants is only ten, but such tendencies as stated below can be confirmed.

・For each patterns, the combinations shown in Figure 9 are distinguishable.

・We reached a hypothesis that vertical stripe is superior in the point of distinguishability.

4. Testing the Hypothesis

4.1. Purpose

To test the hypothesis that vertical stripe is superior in terms of distinguishability

4.2. Method

We built up a hypothesis that the difference of distinguishability comes from the angles formed by stripes and outlines of letters. In order to get the feature value, we approximated the outlines with horizontal lines, vertical lines, and Oblique lines at 45° or 135°. Marching squares algorithm was useful to do this on program. Here is the explanation on marching squares algorithm.

"The marching squares algorithm aims at drawing lines between interpolated values along the edges of a square, considering given weights of the corners and a reference value. Consider a 2D grid as shown in Figure 12 for example.

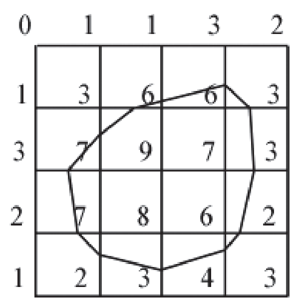

Figure 12. Example of Picture Data

Each point of this grid has a weight and here the reference value is known as 5. To draw the curve whose value is constant and equals the reference one, different kinds of interpolation can be used. The most used is the linear interpolation.

In order to display this curve, different methods can be used. One of them consists in considering individually each square of the grid. This is the marching square method. For this method 16 configurations have been enumerated, which allows the representation of all kinds of lines in 2D space” [8]. (some of the parts are changed)

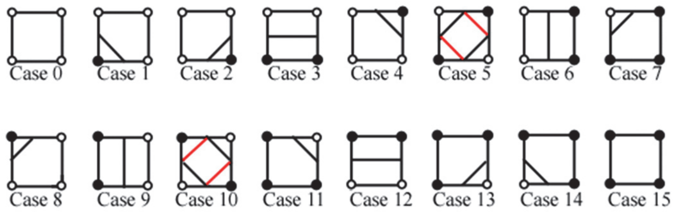

Figure 13. All Patterns of Approximation of Marching Square Method

All of the pictures used in the experiment consist of two colors, so we just considered their weights 1 or 0. By applying Marching Square Method, we made a Java application program and calculated the formed angles. Then, we analyzed the data with discriminant analysis again.

4.3. Analysis and Result

After we calculated the formed angles, we counted the number of each angles (0°, 45°, and 90°), and we weighed the numbers with length, since the ratio of the partial length of 0°, 45°, 90° is 1: $\sqrt{2}$:1. Thus, we made weighed data and analyzed with discriminant analysis.

Tables 8, 9, 10 show whether the parameters are significant or not. Regardless of patterns, both contrast and size are significant, while formed angles are not.

Table 8. Result (Vertical)

Variable	Wilks' λ	F value	Degrees of freedom 1	Degrees of freedom 2	P value	Judgment
Lightness Contrast	0.88	11.89	1.00	84.00	0.00	**
Size	0.92	7.52	1.00	84.00	0.01	**
Parallel	0.97	2.63	1.00	84.00	0.11	
45°	0.99	1.20	1.00	84.00	0.28	
Rectangular	0.98	1.63	1.00	84.00	0.21	

Table 9. Result (Horizontal)

Variable	Wilks' λ	F value	Degrees of freedom 1	Degrees of freedom 2	P value	Judgment
Lightness Contrast	0.74	26.67	1.00	74.00	0.00	**
Size	0.91	7.57	1.00	74.00	0.01	**
Parallel	1.00	0.02	1.00	74.00	0.88	
45°	1.00	0.05	1.00	74.00	0.83	
Rectangular	0.99	0.39	1.00	74.00	0.54	

Table 10. Result (Oblique)

Variable	Wilks' λ	F value	Degrees of freedom 1	Degrees of freedom 2	P value	Judgment
Lightness Contrast	0.83	15.48	1.00	74.00	0.00	**
Size	0.93	5.60	1.00	74.00	0.02	*
Parallel	0.99	1.06	1.00	74.00	0.31	
45°	0.99	1.11	1.00	74.00	0.29	
Rectangular	1.00	0.16	1.00	74.00	0.69	

4.4. Section Conclusions

The formed angles are not able to explain the distinguishability, but the hypothesis is not rejected. Therefore, another way of testing without effect of angles or complexity is needed.

5. Testing the Hypothesis without Effect of Angles or Complexity

5.1. Purpose

Our trial to test the hypothesis by using formed angles failed, but the result implies a test without effects of angles or complexity is ideal, so the purpose of this experiment is to test the hypothesis without effect of angles and complexity.

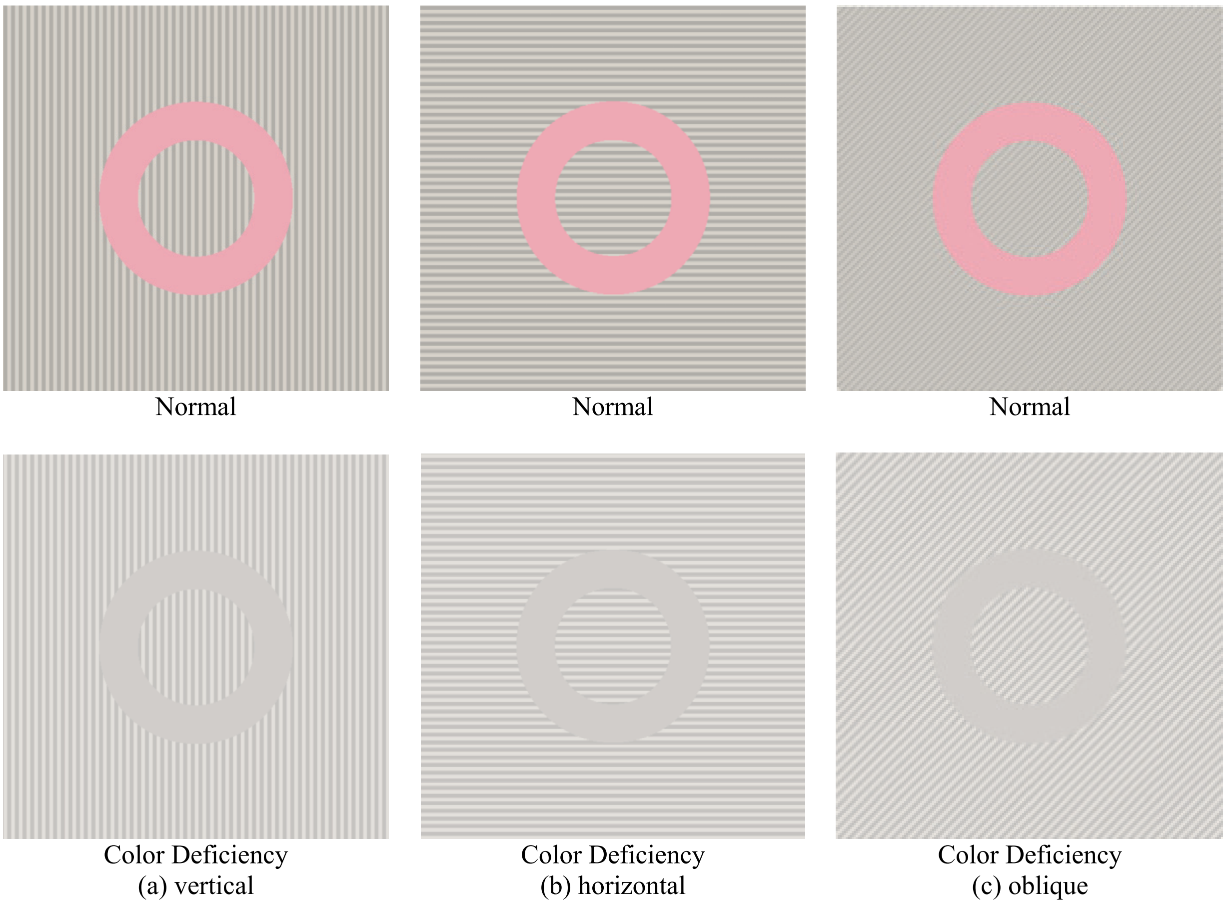

Figure 14. Circle Samples

5.2. Method

Except letters and parameters, all of the conditions are the same. We used circle which has isotropy instead of letters to eliminate the effect of angles and complexity (Figures14, 15). The parameters of dithering are what are distinguishable abstracted by the experiment. We adopted paired comparison method. Estimation is based on the yardstick (Figure16).

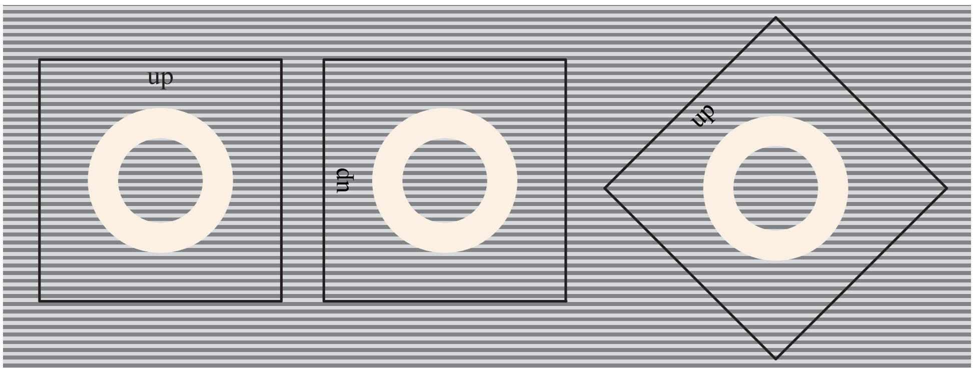

Figure 15. Stripe Orientation in Inkjet Printing

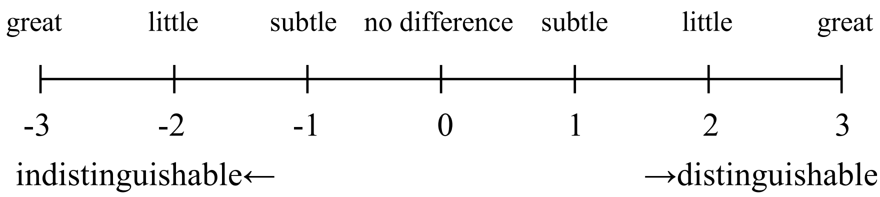

Figure16. Estimation Yardstick

5.3. Analysis and Result

Table 11 shows the result of analysis. Significance of Position means subjects tend to estimate biasedly. In this experiment, the samples are set onto both sides, and the circumstance is line symmetry. Therefore, it can be said that the significance is caused by internal factor. Hereafter, this problem is set aside since important tendency was abstracted and since this neglect can be considered sufficient condition.

Table 11. Result of Analysis of Paired Comparison Method

Factor	Variance	Degrees of freedom φ	Unbiased Variance	F Value	Judgment
Stimulus	2858.98	14.00	204.21	285.99	**
Stimulus*Subjects	8704.82	252.00	34.54	48.38	**
Combination	13.36	91.00	0.15	0.21	
Position	3.55	1.00	3.55	4.97	**
Position*Subjects	11.68	18.00	0.65	0.91	
Error	2580.60	3614.00	0.71		
Total	14173.00	3990.00			

Stimulus was significant, so we put the data into psychological scale (Figure17).

The F test is conducted between each parameter. Look at the data of vertical stripe. On each parameter, vertical stripe is superior to horizontal or oblique stripe. Therefore, we could test and prove the hypothesis.

5.4. Section Conclusions

Dithering of vertical stripe is more distinguishable than that of horizontal or oblique stripe when they have the same lightness contrast and dithering size.

6. Conclusions

- Stripe dithering is efficient in the area shown in Figure 9.
- Dithering of vertical stripe is more distinguishable than that of horizontal or oblique stripe when they have the same lightness contrast and dithering size.
- Designers can use color combinations by using lightness contrast dithering method, and especially vertical stripe is more distinguishable by people with color vision deficiency, while the dithered color approximates the original solid color.

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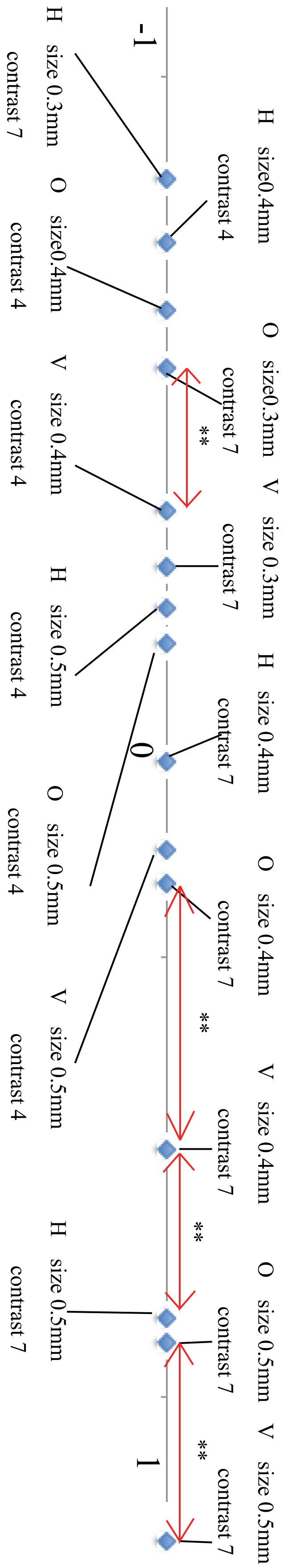

Figure17. Result of Psychological Scale

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[8]< http://users.polytech.unice.fr/~lingrand/MarchingCubes/algo.html>[Accessed 9 March 2013]