A meta-analysis of color palettes for protans and deutans: The problems with using dichromatic simulations

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Abstract

This study describes a meta-analysis of three color palettes for protans and deutans, respectively proposed by Tol (2012), Krzywinski et al. (2012), and Ito et al. (2013). Their three color palettes were defined using standard red-green-blue (sRGB) tristimulus values, and they were designed to help color-deficient people distinguish the colors of graphs, maps, and other visual representations. However, color differences between the component colors of their palettes and the chromatic distribution of the component colors were unspecified by these researchers. Without comparative studies, it is difficult to compare the performance of these palettes and their visual effectiveness for color-deficient people. Hence, this study provides a meta-analysis of their color palettes. Protanopic and deuteranopic color perception and color differences were used for this analysis, along with a combination of a dichromatic simulation method and a uniform color space, such as CIELAB and CIELUV. This study elucidates a problem for analyses that rely on dichromatic simulation methods calculated using the reduced stimuli planes in the RGB color space, and proposes a way around such simulations. The results of the meta-analysis reveal that the three color palettes have problems in terms of the uniformity of color difference and the chromatic distribution of the component colors.

1. Introduction

Color-vision deficiencies, such as protanopic and deuteranopic deficiencies, occur when the cells in the human retina fail to function normally or lack certain types of cone cells. In many cases, the dysfunction is caused by specific genetic factors that affect a considerable number of people. In the USA, for example, approximately 7% of males and 0.4% of females suffer from either protanopic or deuteranopic color-vision deficiency. Globally, more than 200 million people suffer from some form of congenital color-vision deficiency. Such people have difficulty distinguishing particular sets of colors. For example, protanopic and deuteranopic people often confuse red with green, deep red with black, pink with sky blue, blue-green with gray, and pea green with yellow. These particular sets of colors are called “confusion colors.”

In order to avoid using confusion colors for graphs, maps, and other visual representations, so-called “protanopic/deuteranopic-safe” (p/d-safe) color palettes have been proposed. Ichihara et al. [1] were the first to propose the idea of a p/d-safe color palette. Harrower and Brewer [2], Tol [3], Krzywinski et al. [4], and Ito et al. [5] then proposed original p/d-safe color palettes independently. Each color palette comprises at most 20 previously selected colors. Ichihara et al. [1] described the results from a visual experiment on color categories perceived by protanopic, deuteranopic, and normal (trichromatic) vision observers, and they present a justification for the decision to include the four component colors that comprise their color palette. However, recent propositions by Tol [3], Krzywinski et al. [4], and Ito et al. [5] did not include a justification for their component colors. These p/d-safe color palettes are easy to use for map designs, graph designs, package designs, web-page designs, and so on, in accommodating protanopic and deuteranopic people, but it is difficult to compare their palettes in terms of their performance and visual effectiveness for color-deficient people.

The meta-analysis in this study compares previously proposed p/d-safe color palettes on the basis of the uniformity of color differences and the chromatic distribution of component colors. Conventional analyses of the color differences and the chromatic distribution perceived by protanopic and deuteranopic people were done using a combination of a dichromatic simulation method—such as the methods proposed by Brettel et al. [6], Viénot at al. [7], or Ito and Maekawa [8]—and a uniform color space (such as CIELAB or CIELUV). These analyses were used in Ichikawa et al. [9], Nakauchi and Onouchi [10], Meguro et al. [11], and several others.

This article uncovers a problem with conventional analyses concerning the estimation of color differences and chromatic distribution perceived by people with protanopic and deuteranopic color vision. Instead, a more appropriate way to estimate protanopic and deuteranopic color differences and the chromatic distribution is proposed. The proposed method deals directly with a long-medium-short (LMS) cone response—as described in Brettel et al. [6]—and both protanopic and deuteranopic color differences along with the chromatic distribution are estimated using a proposed quasiuniform color space ($L^{\#}M^{\#}S^{\#}$).

2. Materials and Methods

2.1 P/d-safe color palettes

This study deals with three p/d-safe color palettes, proposed respectively by Tol [3], Krzywinski et al. [4], and Ito et al. [5]. Their three color palettes were defined using sRGB tristimulus values—described in IEC 61966-2-1 [12]—as shown in Tables 1, 2, and 3. These palettes are designed to help color-deficient people distinguish colors in maps, graphs, packages, webpages, and so on.

The color palette proposed by Tol [3] comprises nine colors (two light colors, three dark colors, and four medium colors). Tol [3] was published as a technical note from the Netherlands Institute for Space Research (SRON), and the sRGB tristimulus values for its component colors were described therein.

The color palette proposed by Krzywinski et al. [4] comprises 15 colors (five colors perceived as bluish, five colors perceived as yellowish, and five colors perceived as medium colors by protans and deutans). Krzywinski et al. [4] proposed their color palette at a symposium on biological data visualization (Biovis 2012). Their description and the sRGB tristimulus values for the palette were included on the poster they presented at Biovis 2012, but their paper in the proceedings for Biovis 2012 did not include a description of their proposed color palette. Importantly, the sRGB tristimulus values described in Krzywinski et al. [4] must be

Table 1. Color palette by Tol [3], with nine colors (light, dark, and medium colors).

Tol (2012)	sRGB tristimulus values (8bits)											
	R	G	B	R	G	B	R	G	B	R	G	B
Light Colors	136	204	238	221	204	119						
Medium Colors	68	170	153	153	153	51	204	102	119	170	68	153
Dark Colors	17	119	51	136	34	85	51	34	136			

Table 2. Color palette by Krzywinski et al. [4], with 15 colors (bluish, yellowish, and medium colors).

Krzywinski et al. (2012)	sRGB tristimulus values (8bits)														
	R	G	B	R	G	B	R	G	B	R	G	B	R	G	B
Medium Colors	0	0	0	0	73	73	0	146	146	255	109	182	255	182	219
Bluish Colors	73	0	146	0	109	219	182	109	255	109	182	255	182	219	255
Yellowish Colors	146	0	0	146	73	0	219	109	0	36	255	36	255	255	109

Table 3. Color palette by Ito et al. [5], with 20 colors (vivid and strong, soft and pale, and achromatic colors)

Ito et al. (2013)	sRGB tristimulus values (8bits)																										
	R	G	B	R	G	B	R	G	B	R	G	B	R	G	B	R	G	B	R	G	B	R	G	B	R	G	B
Vivid & Strong Colors	255	40	0	255	153	0	250	245	0	53	161	107	102	204	255	0	65	255	154	0	121	255	153	160	102	51	0
Soft & Pale Colors	255	209	209	237	197	143	255	255	153	203	242	102	135	231	176	180	235	250	199	178	222						
Achromatic Colors	255	255	255	200	200	203	127	135	143	0	0	0															

corrected, because the sRGB tristimulus values for No. 5 are misprinted, where (255, 182, 119) should read (255, 182, 219). Likewise, No. 13 (219, 209, 0) is a misprint for (219, 109, 0).

The color palette proposed by Ito et al. [5] comprises 20 colors (nine vivid and strong colors, seven soft and pale colors, and four achromatic colors). Ito et al. [5] also proposed two alternative colors, but, for the sake of simplicity, our study does not address them. Ito et al. [5] is published in Japanese. Recently, Sakamoto [13] revealed that the color palette proposed by Ito et al. [5] could be applied to image processing to replace confusion colors.

2.2 Protanopic and deuteranopic simulation methods

Brettel et al. [6] simulate protanopic and deuteranopic perceived colors using RGB colors. Brettel et al. [6] proposed reducing the stimuli plane folded from an equal-energy line in the RGB color space. Their proposal allows for protanopic and deuteranopic color perception in the form of RGB images.

Viénot at al. [7] also simulate protanopic and deuteranopic perceived colors using RGB colors. Viénot at al. [7] also proposed a reduced stimuli plane, yet one that is not folded from an equal-energy line in a RGB color space.

The simulation method proposed by Ito and Maekawa [8] was adopted by Adobe Systems Incorporated, and now runs on Adobe Photoshop-CS4, -CS5, -CS6 and later versions. There is no detailed documentation available on their simulation algorithm, but the basic concept for their simulation method is described (in Japanese) on their webpage [14].

2.3 CIELAB and $L^{\#}M^{\#}S^{\#}$ color spaces

The CIELAB color space is a perceptually uniform and standard color space—viz., the CIE 1976 color space, as documented in Hunt [15]—and represents color differences by the Euclidean distance between colors. CIELAB has three orthogonal axes: L*, a*, and b*. The lightness L* represents the darkest black at zero and the brightest white at 100. The a* and b* axes represent the degrees of chromaticness, and the achromatic colors at $a^* = 0$ and $b^* = 0$.

CIELAB can evaluate the color differences perceived by normal (trichromatic) color vision, but cannot immediately deal with color differences perceived by protanopic and deuteranopic vision. Therefore, it is necessary to combine a dichromatic simulation method with the CIELAB color space, but this combination lacks precision, because the simulation method is only an approximation of the protanopic and deuteranopic views.

To avoid the approximation that arises from a protanopic and deuteranopic simulation, this study utilizes the LMS color space, because it can accommodate and indicate protanopic and deuteranopic views of colors immediately in the form of tristimulus values. However, another issue is pertinent to the color difference: the LMS color space is not perceptually uniform. In order to overcome this issue, this study uses a quasiuniform color space, $L^{\#}M^{\#}S^{\#}$, and utilizes it for an analysis of the chromaticity distribution colors. $L^{\#}$ is a nonlinear transformation of the L axis in the LMS color space, and it is obtained by using the same nonlinear formula for the L* axis in the CIELAB color space. $M^{\#}$ and $S^{\#}$ are also obtained using a similar procedure for the M and S axes of the LMS color space.

3. Results and Discussion

3.1 Chromaticity distribution represented by CIELAB color space and three simulation methods

Figure 1 shows the chromaticity distribution map using the CIELAB color space. Figures A and B show the chromaticity distribution map along the a* and b* axes, and L* and b* axes, respectively. The color differences between each color are represented as the Euclidean distance in the CIELAB color space.

Figures A-1 and A-2 show the original chromaticity distribution (i.e., as perceived by normal color vision) for the nine colors proposed by Tol [3]. Diamonds represent light colors, triangles represent medium colors, and squares represent dark colors in the color palette.

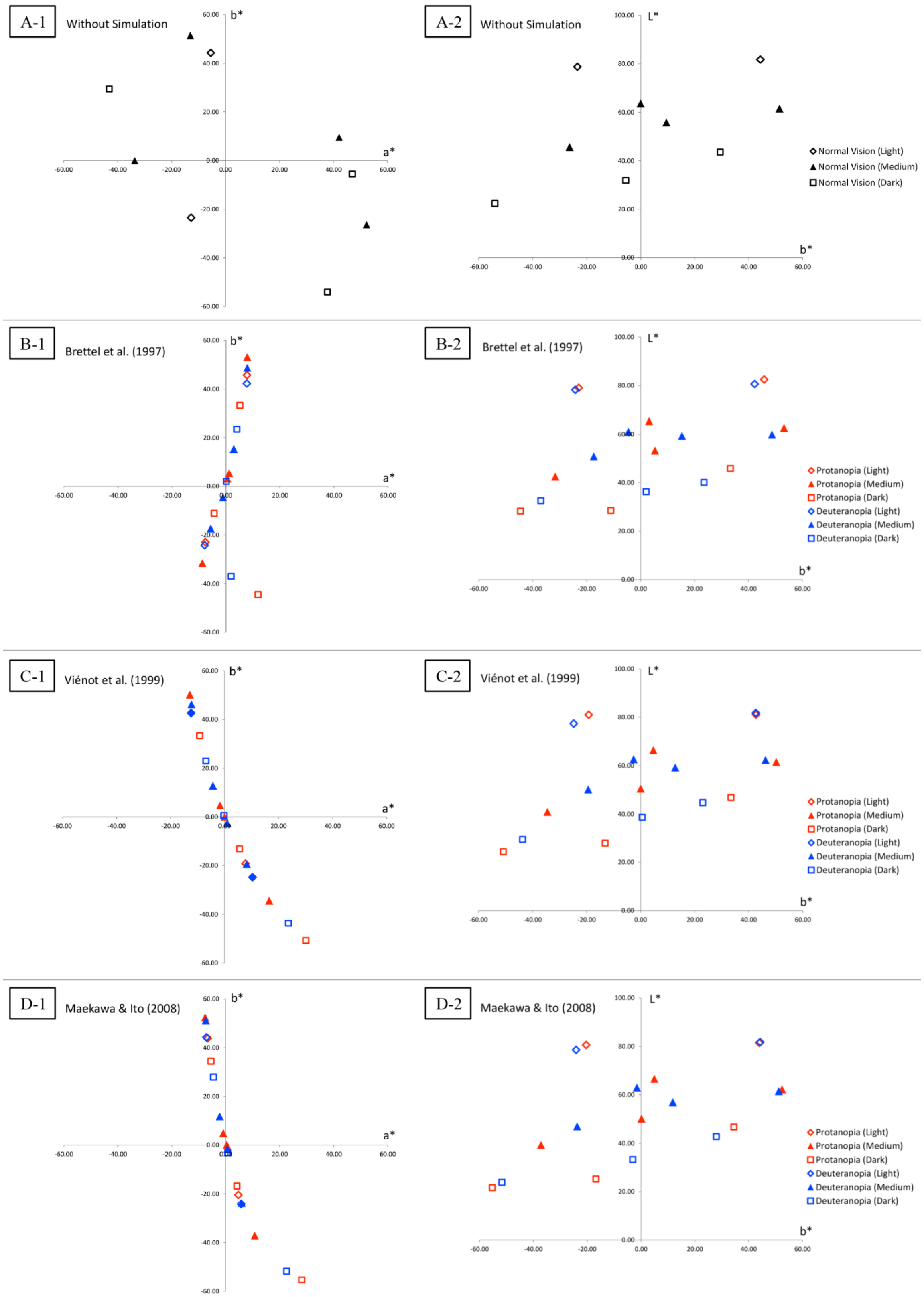

Figure 1. CIELAB chromaticity distribution along the a and b* axes (A-1, B-1, C-1, and D-1), and L* and b* axes (A-2, B-2, C-2, and D-2). Figures B, C, and D show the simulations by Brettel et al. [6], Viénot at al. [7], and Ito and Maekawa [8], respectively. The red and blue dots represent protanopic and deuteranopic simulations, respectively.*

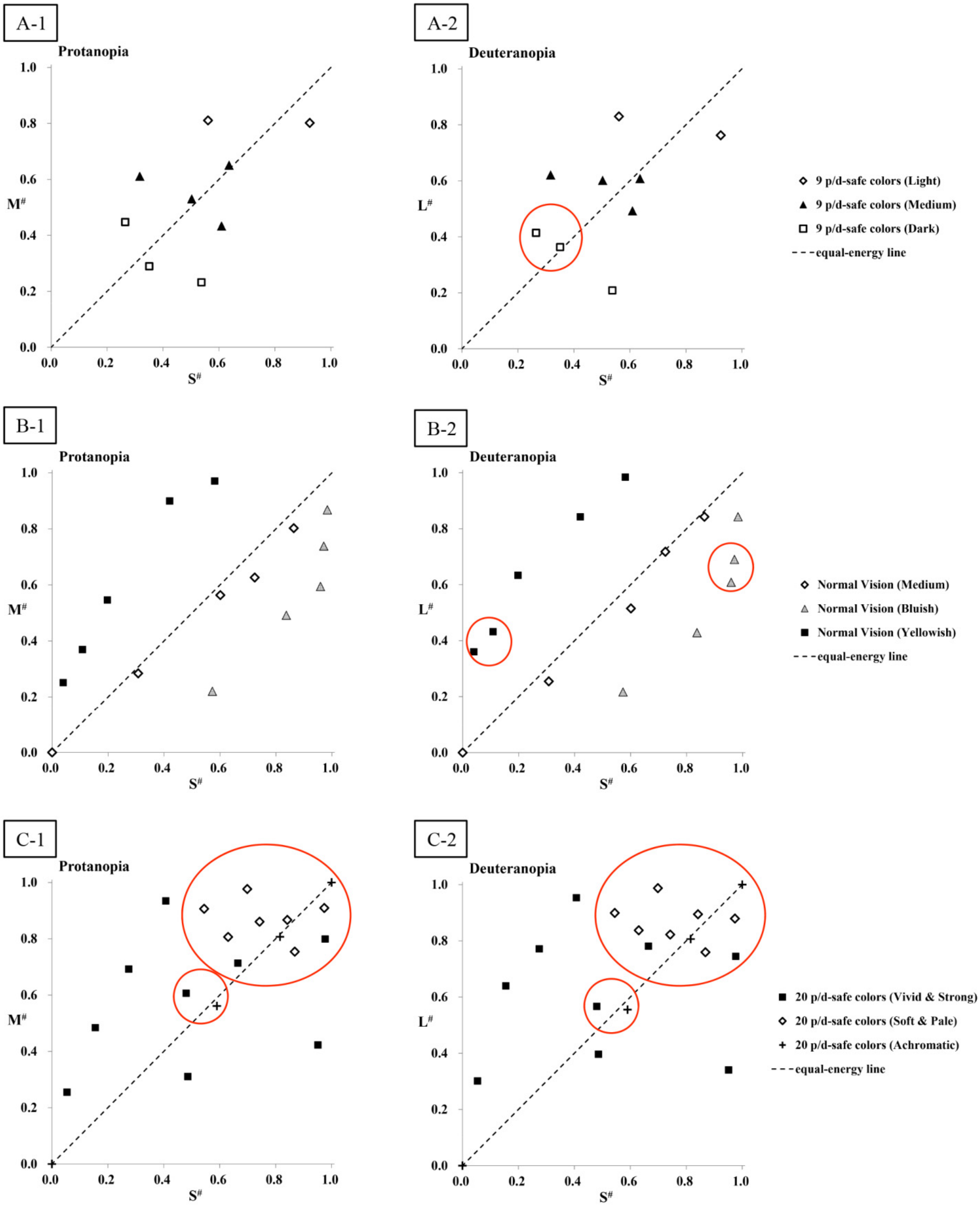

Figure 2. Chromaticity distribution along the $L^{\#}$, $M^{\#}$, and $S^{\#}$ axes. Figures A, B, and C show chromaticity distribution of the p/d-safe color palettes proposed by Tol [3], Krzywinski et al. [4], and Ito et al. [5], respectively. Figures A-1, B-1, and C-1 directly represent protanopic perception, and Figures A-2, B-2, and C-2 directly represent deuteranopic perception. The red circles indicate that the color differences between the dots are too small by comparison with others.

Figures B, C, and D show the chromaticity distribution after applying the protanopic and deuteranopic simulation by Brettel et al. [6], Viénot at al. [7], and Ito and Maekawa [8], respectively. Red and blue dots represent the simulated protanopic and deuteranopic chromaticity distribution, respectively. Again, diamonds, triangles, and squares represent light, medium, and dark colors, respectively.

It is obvious that the chromaticity distribution changes dynamically according to the change of simulation methods, and this is clear from Figures B-1, C-1, and D-1. These results suggest that the color differences estimated from Figures B, C, and D may change drastically depending on the simulation method, and it is obvious that estimating color differences using a combination of a dichromatic simulation and CIELAB lacks considerable precision.

3.2 Analyzing the chromaticity distribution using $L^\# M^\# S^\#$

Figure 2 shows the chromaticity distribution maps for the component colors used in the p/d-safe color palettes proposed by Tol [3], Krzywinski et al. [4], and Ito et al. [5]. The left-side distribution map describes the protanopic perception of colors using the $M^\#$ and $S^\#$ axes, and the right-side distribution map describes deuteranopic perception of colors using the $L^\#$ and $S^\#$ axes. The dashed lines represent the ideal achromatic line (i.e., the equal-energy line).

Figures A, B, and C represent the chromaticity distributions for component colors by Tol [3], Krzywinski et al. [4], and Ito et al. [5], respectively. It is obvious that the color differences between the palettes' component colors are relatively conspicuous in Figures A and B. However, many colors in Figure C have insufficient color differences between them.

Figures C-1 and C-2 suggest that vivid and strong colors have more color distance between each other than soft and pale colors, which suggests that soft and pale colors are more difficult to distinguish amongst each other. These figures also suggest that achromatic colors, such as pale gray and gray, have less color distance between soft and pale colors and a vivid and strong color. Ito et al. [5] propose the palette with the most number of colors, yet the chromaticity distribution must be optimized from the perspective of color difference.

It is also obvious that there are few low-lightness colors in Figures C-1 and C-2. Thus, the number of low-lightness colors, such as deep blue and deep green, should be increased. On the other hand, the number of soft and pale colors seems to be too high to easily distinguish between them. Soft and pale colors, and gray, should be redesigned for uniformity to the color differences between each color.

4. Conclusion

A meta-analysis of the three color palettes respectively proposed by Tol [3], Krzywinski et al. [4], and Ito et al. [5] revealed the following results: First, a combination of a dichromatic simulation method and a uniform color space such as CIELAB is unsuitable for analyzing color difference as perceived by dichromatic observers, and for the chromatic distribution of perceived colors. Second, from a meta-analysis using a quasiuniform color space, $L^\# M^\# S^\#$, the three color palettes revealed problems concerning color differences and the chromatic distribution of their component colors. An optimization of color differences and the chromatic distribution of a p/d-safe color palette will be subjects of interest for our research in the near future.

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