Quality of color coding in maps for color deficient observers

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Abstract

For a color deficient observer, the quality of a map or other information design may be defined as the ability to extract features. As color is such important conveyor of information, the colors need to appear correct and be perceived in the desired and intended way. As color appearance is affected by the size of the stimuli, the task of discriminate colors may be even more difficult for a color vision deficient observer.

In order to investigate the discriminability of the color coding in an official Norwegian map product, we conducted an experiment involving both color deficient and color normal observers. Also, we investigate to what extent the ability to discriminate colors is influenced by size of the visual field.

The experiment revealed that the color vision deficient observers made significant more errors than the normal observers, especially when the visual angle was reduced.

Introduction

It is established that color is undoubted guide to visual attention [1]. Color vision deficiency (CVD) is a condition that affects the ability to distinguish and discriminate colors, and it is believed that about 8% of all males and 0,5 % females is affected by such condition [2, 3]. Studies reviewed in the work of Cole [4] reveal that up to 60% of the users with abnormal color vision reported problems in observational task as reading color coded charts, slides and prints. Further, they are slower and make more errors in search when color is an attribute of the target object or is used to organize the visual display.

It is well known that the color appearance is affected by size of the stimuli, which is often referred to as the color size effect. Carter and Silverstein [5] state that a common experience is difficulty discriminating the multiple small-subtense colors on weather, financial, and other maps and charts viewed on print media and conventional-size information displays.

Color is a cartographic element that is used both aesthetically and as a conveyor of information and is well documented in literature [6-9]. Color is the cartographic element that is most frequently misused and is often considered as a difficult cartographic element to use, as it easily draws attention away from the data and goals for the map when it is used poorly [8].

Based on the assumption that quality of a map can be based on the ability for a user to extract features, the main goal in this study is to investigate the following research questions:

- Are the colors in an official Norwegian map product distinguishable for a color deficient observer?
- Is the ability to distinguish or recognize colors more influenced by variation of visual angle for color deficient observers compared to observers with normal color vision?

The paper is organized as follows: First, an overview of basic concepts and related work necessary to understand the research topic is given. Then the experimental setup is described, followed by results, discussion and conclusion.

Background and related work

This section gives an overview of some of the basic concepts and related work which are essential for the understanding of this research topic. An overview on cartography and color coding, color vision deficiencies, color size effect and visual field is provided in the following pages.

Maps and cartography

In reference maps, hue is used to symbolize different kinds of features like the blue and green for water and land. Color may be used to represent qualities or quantities and often in a combination, like a topographic map will use hue in order to present qualitative data (like water) or classify data (like class of roads) and value to classify and represent quantitative data (like deepness of the water).

Bertin [9] states that "Above all, color exercises an undeniable psychological attraction. In contrast to black-and-white it is richer in cerebral stimulation, and in numerous cases where it can appear as a luxury, this luxury nonetheless "pays off". It captures and holds attention, multiplies the number of readers, assures better retention of the information, and, in short, increases the scope of the message. Color is particularly applicable to graphic messages of a pedagogic nature".

The use of color in maps is most based on conventions and traditions. Some of the conventions are to choose colors that have a similarity to real life objects, like green and blue to represent land and water. Other conventions are to use strong colors to emphasize important objects, like the use of red to represent highways or cities. Standards or specifications exists for thematic maps in different industries like geology [10, 11], hydrographic services and nautical charts [12] and sports like orienteering [13, 14]. There is also a standard from the International Standardization Organization, ISO 19117:2012 Geographic informations - Portrayal [15]. This standard handles presentation of geographic data, but the focus is more on symbolization than use of colors. Then there are the national standards or specifications (often adopting on the ISO 19117), like the standard of the Norwegian Mapping Authority [16] and the specification for cartography on digital displays [17].

Color vision and color deficiency

Trichromacy is the ability to perceive colors through the three types of cones (L, M and S) that respond to different wavelengths of the visible spectrum. People with full color vision perceive color with all three cones, while people with different color vision anomalies are affected by either a lack of or dysfunction of one or more of the cones. Color vision deficiencies are most often a congenital condition, but may also be caused by medical conditions.

Color vision deficiencies are well described in literature, for example in the book by Hansen [2]. As for the classification of the color vision it is categorized according to available cones (monochromatism, dichromatism and anomalous trichromatism) and further categorized by the cones that are missing or dysfunctional:

- Protanopia or Protanomaly (missing or dysfunctional L-cone (red)).
- Deuteranopia or Deuteranomaly (missing or dysfunctional M-cone (green)).
- Tritanopia or Tritanomaly (missing or dysfunctional S-cone (blue)).

A missing or dysfunctional cone does not make the observer "color blind", but the color perception is limited and the observer may have problems perceiving certain colors accurately and may confuse color ranges.

Image enhancement methods for color vision deficient observers

A typical method for enhancing images to improve their quality for CVD observers [18] is to change the color (re-coloring methods). Specializations of such methods are the daltonization methods, aiming to compensate poor color discrimination by targeting a specific type of CVD. An overview of existing methods and evaluation of these by measuring accuracy and response time in sample-to-match and visual search methods involving CVD are well described in the work of Simon-Liedtke et al. [19]. Other examples of re-coloring methods is the palette method proposed by Green [20] and a version of the palette method applied to maps proposed by Kvitle et al. [21].

Simulations of different color deficiencies and daltonization methods have been applied in order to create better maps for the CVD observer. The ColorBrewer [7, 22] and Colororacle [23], both based on algorithms like those described in Brettel et al. [24] are examples of applications dedicated to maps. One major problem with simulations is that they operate more like a guideline for a designer with normal color vision. The ColorBrewer is evaluated by CVD observers in experiments involving multiple choice map reading questions as described in the work of Gardner [25], but in a limited group of subjects. The color palettes described in ColorBrewer are well suited for thematic mapping such as choropleth maps, but are not directly applicable to the common reference map (which is the aim of our study) because of the limited set of colors. The Ordnance Survey [26] has developed new reference maps for CVD observers, where the maps are actually developed in an iterative way in cooperation with CVD observers. The group of ten CVD observers was recruited among employees, and these users contributed in several phases of the development. These maps have been embraced by both CVD and color normal observers, even though some of the color coding are unconventional.

Color size effect and visual angle

The visual angle [27] or the object's angular size is the relationship between the viewing distance and the size of the object. Years of research states that color appearance changes according to different sizes of the same color stimulus. An overview of history of this research and a structural model is given in the work of Carter and Silverstein [5]. An attempt to take this effect into account in the CIECAM02 color appearance model is described by Luo and Li [28] and experimental work on variation of size on display are described in Xiao et al. [29].

Exploring the color size effect for CVD observers, like the work of Pokorny and Smith [30], Nagy et al. [31] and Paramai et al. [32] indicate a correlation between stimulus size and performance in color-naming tasks as many dichromats show trichromacy in color matching and name the colors in fair agreement with the normal observers in larger fields of view (≥3°). Also, the experiments [31] revealed large individual difference between the observers and that for some observers the ability to discriminate varied considerably as a function of the stimulus parameters, such as field size, luminance level and method of presentation. As summarized in Pokorny and Smith [30], in large fields dichromats show weak residual trichromatic vision and at higher luminances deuteranopes and protanopes show residual deuteranomaly and protanomaly.

Experimental work

Based on the goals to test if the colors of a known official map are discriminable for CVD observers, and if color size effect is larger for these observers, an experiment was set up and conducted.

Visual assessment

The experiment was designed as a four-alternative forced-choice experiment using the assessment tool QuickEval [33], giving the instruction "Select from the small patches (legend) on the right side the color that match the larger color patch on the left. Give your score using the dropdown box". An example of such sample is illustrated in Figure 1.

The matching color was selected by a dropdown menu with four categories (category 1, 2, 3 and 4) named "Top", "Second from the top", "Second from the bottom" and "Bottom" in the dropdown list. Selection was confirmed by clicking the "Next"-button in the right corner. The observers were encouraged to comment while they were doing the task. The comments were recorded by the authors during the experiment.

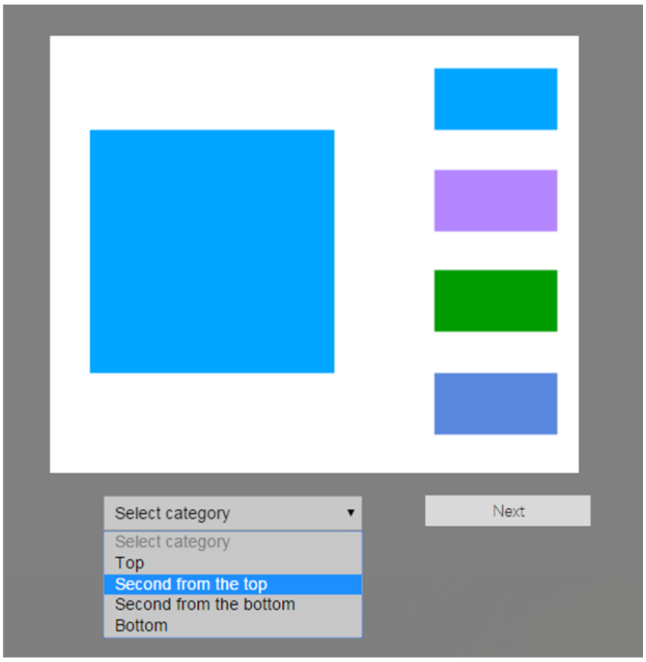

Figure 1: *Illustration of a sample as presented in the QuickEval experiment too.l*

Sample preparation

Colors from the specification for N50 Kartdata [17, 34] map series in the scale 12:000 to 40:000 were chosen and used in 16 images containing a patch of 208 x 208 pixels, giving a visual angle of 6.4° based on the distance of 50 cm between the observer and display. In addition to the colors from the N50 Kartdata, four colors (two different greens, red and yellow) from the universal design portal Tilgjengelighetsportalen were used in one of the images. The colors and coding used in this experiment are found in Appendix A.

In addition to the reference patch, four colors were presented in the style as a legend on a real map: small rectangles in a column on the right of the patch as illustrated in Figure 1.

For each of the 16 images, 3 versions were made with different size of the legend elements. A common legend object size of a printed map would give a visual angle of 2.3° based on the distance between the observer and the display. To vary the visual angle, versions with 3.5° and 1.2° corresponding to a difference of 1 cm of each of the legend objects.

The colors and combination of colors were selected by the arguments of:

- Extensiveness (how often the color is used, typically areas).
- Probability to appear related to each other or in the same map image (industrial buildings will appear in urban areas, not in the forest).
- Combinations assumed to be difficult for a color deficient user (red road on green background).

The colors were categorized according to the object they would represent (area, line or point), and combinations in the images may be colors representing different areas (urban, land, sea, non-forested areas etc.), different lines (borders, roads, rivers etc.), different objects (private house, cottage, industrial buildings etc.) and combinations of area and lines and/or objects.

The combinations of colors that assumed to be difficult for a CVD observer were selected by two different approaches:

1. By common assumptions like confusing red and green colors.
2. Simulation of protanope and deuteranope color vision of the colors that were likely to appear in a map.

Except for the attempt to separate colors that could be confused with another color in between, the order of the colors in the legend was random for each image (but not random between the observers).

The background color affects the ability to discriminate colors. As the background of a map legend is usually white the background color was set to white, while the default grey color in QuickEval was kept unchanged.

Observers

21 observers (4 female and 17 male) participated in the experiment. 7 of the observers (all male) are tested and confirmed to have a reduced color vision while 14 observers are either assumed to have or tested to have normal color vision. All the CVD observers are tested with the Ishihara test plates [35], the HRR color vision test [36], the Farnsworth D15 hue tests [37] and the Lanthony D15 Desaturated Hue test [38]. As these tests are not accurate enough to separate the extensiveness of the CVD (i.e deuteranope and deuteranomaly) and therefore the observers in this experiment are generalized and referred to as protanope and deuteranope observers. Of the 7 observers, there are one protanope and six deuteranopes.

Display and physical environment

The experiment was conducted on a sRGB calibrated NEC SpectraView LCD 2180WG with a 1600 x 1200 resolution, calibrated with an Eye-One spectrophotometer and Eye-One Match software to determine the display whitepoint of 6500K and gamma of 2.2. Distance between the observer and display was 50cm. The light in the room was dimmed, and measured to approximately 30 lux in front of the display.

Data analysis

The Pearson's N-1 Chi-Square test [39] is suitable for comparing groups, as we want to compare (i) if the colors are distinguishable for a CVD observer (compared to a normal observer), and (ii) if the variation of size affect the CVD observer more than a normal observer.

Results

The results of the experiment are presented and discussed in the following order: First overall results of all observers, colors and visual angle. Then a comparison of the observer groups, based on correctness and visual angle is given before comparing the visual angles within each group.

Details of the images and corresponding non-correct assessments will be presented in this section. Based on the number of non-correct assessments and distribution among the observers (based on color vision), the images with errors are categorized as and presented in the following order:

- Difficult images for all observers
- Difficult for CVD observer
- One-error images (possible typo = selected wrong in the drop down list).

The image set consists of 16 images in 3 different variations giving a visual angle of 3.5°, 2.3° and 1.2°. From these 16 images, errors were made in 7 of them based on the observers' ability to match the patch. Results from these seven images are summarized in Table 1, illustrating the total numbers of non-correct selections for each image. Further, the non-correct assessments for each visual angle version are given, and also categorized by the color vision of the observer. As illustrated in Table 1, the number of non-correct selections for each image varies from 1 to 11, and increases as the visual angle decreases. Also, all of the CVD observers made at least one non-correct assessment and there is a variation of non-correct selection (from one and up to 8) as summarized in Table 2.

In order to quantify the color differences between the reference color and three non-matching legend patches in each image, distance between colors can be computed in the CIELAB color space. Such distance metric is referred to as the ΔE^*_{ab}, and computes the distance between two colors based on the L*a*b* in the CIELAB color space. In this paper we use the CIEDE2000 color difference equation and the ΔE_{2000} color difference. Background and further details about CIEDE2000 may be found in Luo and Rigg [40].

Further, to investigate more details of the color difference, the difference in lightness ΔL^* is also computed. The ΔE_{2000} and ΔL^* found and the corresponding non-correct assessments are summarized Table 3, and it should be noted that some of the images have more than one non-correct assessment of the legend patches.

Table 1: Non-correct assessments, categorized by image version (3.5°, 2.3° and 1.2°) and color vision (protanope (P), deuteranope (D) and normal (N) color vision observer).

		Non-correct assessment on images:									
		Visual angle									
		3.5°			2.3°			1.2°			Total
		P	D	N	P	D	N	P	D	N	
Image number	1		3	2			2		3	1	11
	2	1			1			1			3
	3								1		1
	4		1		1	2		1	3		8
	5		1			1			1		3
	6					1	1				2
	7								1	1	2
Sum:		8			9			13			30

Table 2: Non-correct selections made by CVD observers, sorted by individual observer (P = protanope, D = deuteranope). All the CVD observers had non-correct selections, varying from one to 8 and the number of non-correct selections increases as the visual angle decreases.

		Non-correct assessment on images:			
		Visual angle			
		3.5°	2.3°	1.2°	Total
Observer number	#4 (P)	1	2	2	5
	#5 (D)	2	3	3	8
	#6 (D)			3	3
	#7 (D)		1	2	3
	#8 (D)	1		1	2
	#14 (D)	1			1
	#19 (D)	1			1
Sum:		6	6	11	23

Table 3: The color difference ΔE_{2000} and lightness difference ΔL^* between the reference and non-matching legend patches for the images with non-correct assessments.

Image number	ΔE_{2000}	ΔL^*	Non-correct
1	3,4	3,5	11
	17,2	17,4	
	74,3	10,1	
2	23,8	7,4	3
	17,4	17,3	
	47,3	11,0	
3	10,8	7,5	1
	14,0	11,0	
	23,8	7,4	
4	7,9	2,9	8
	43,3	29,5	
	20,0	22,7	
5	29,5	0,2	2
	59,7	9,5	
	13,5	8,5	1
6	27,7	32,0	1
	74,3	10,1	1
	53,6	2,5	
7	8,8	8,3	
	23,9	10,2	
	13,9	3,2	2

When comparing color difference ΔE_{2000} and number of non-correct selections, the scatter plot in Figure 2 (which also includes ΔE_{2000} for all 16 images) indicates a relation between the number of non-correct selections and the color difference. As illustrated in the plot, the largest number of non-correct selections are for color differences below 10.

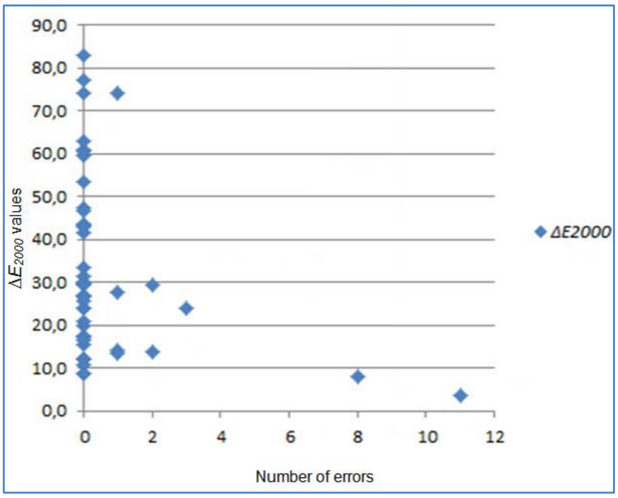

***Figure 2:** Comparing color difference (ΔE_{2000}, y-axis) and number of non-correct selections (x-axis) for all 16 images.*

Further, when comparing lightness difference ΔL^* and number of non-correct selections, the scatter plot in Figure 3 (which also includes ΔL^* for all 16 images) indicates a relation between the number of non-correct selections and the lightness difference. Here the largest number of non-correct selections are for lightness differences below 5.

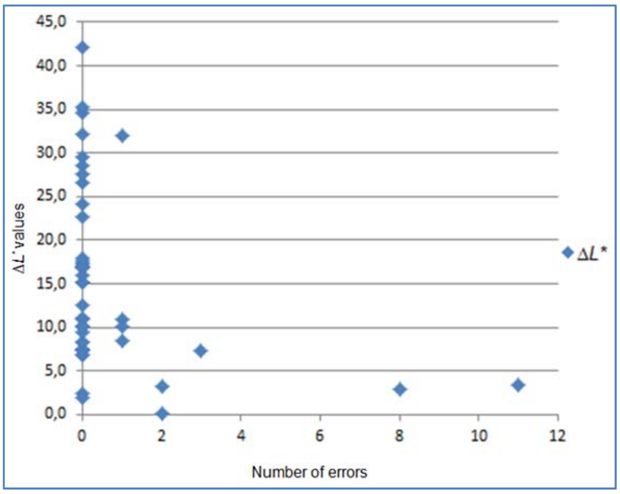

***Figure 3:** Comparing lightness difference (ΔL^* y-axis) and number of non-correct selections (x-axis) for all 16 images.*

Difficult images

Difficult images are images with many non-correct selections and the selections are made by both CVD and normal observers.

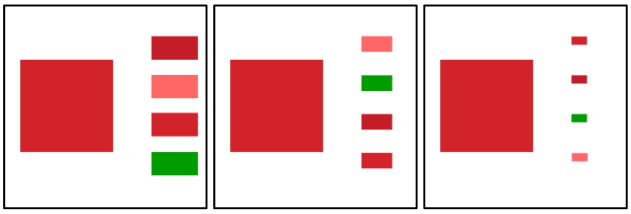

Figure 4: The 3.5°, 2.3° and 1.2° (left, middle, right) versions of image number1. This image was difficult for all observers.

Image number 1 (Figure 4) was reported to be difficult for all observers, confusing the red colors (category 1 and 3 in the legend in the left image). Most of the observers commented that the red colors were very similar, and that selected color was based on guessing rather than seeing a difference. As reported in Table 3, both the ΔE_{2000} and the ΔL^* are fairly small (3.4 and 3.5).

Difficult for CVD observers

Image number 4 (Figure 5) was difficult for several of the CVD observers, as 5 of the observers had at least one non-correct selection (confusing category 1 and 3 in the legend in the left image). The total number of non-correct assessment in this image is 8, as reported in Table 1. The ΔE_{2000} between the in confusing colors in this image larger than in image 1 (7.9 versus 3.4), but the ΔL^* is small (2.9).

Figure 5: Image number 4 was difficult for the CVD observers. 5 of the observers made a total of 8 non-correct selections.

The following images were difficult for CVD individuals, as the non-correct selections in each image (including all three versions) were made by an individual observer.

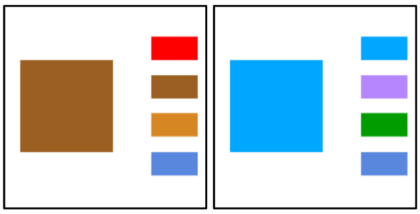

Figure 6: Image number 2 (left) and image number 5 (right) were difficult for CVD individuals.

Observer #4 confused the red and brown (category 1 and 2 in Figure 6, left) in image number 2 for all 3 versions. It should be noted that the same red and brown colors are used combined with 2 other reds in image number 3, where this observer had no mistakes, as shown in Table 1. The ΔE_{2000} is between the brown and red color is 23.8 and the ΔL^* is 7.4.

Image number 5 (Figure 6, right) was difficult for observer #5, confusing the purple color and blue color (category 2 and 1) and then confusing the blue colors in the 1.2° image. While the ΔE_{2000} is high (29.5), the ΔL^* is only 0.2 for the blue and purple color, and ΔE_{2000} is 13.5 and ΔL^* is 0.5 for the blue colors.

One-error images

3 of the images had only one non-correct assessment, or two non-correct assessments made by two different observers. These images are presented in Figure 7. One of the CVD observers confused the red colors (category 2) in the 1.2° version of image number 3 (Figure 7, left). In the 2.3° version of image number 6 (Figure 7, middle), a CVD observer selected the red color (category 3), while a color normal observer selected the light green (category 1). In the 1.2° version of image number 7 (Figure 7, right), two observers (one CVD and one color normal) selected the lightest yellow (category 3).

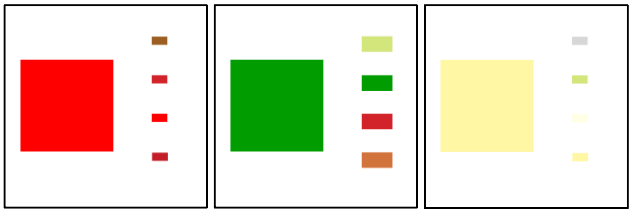

Figure 7: Image number 3 (left), number 6 (middle) and number 7 (right) had one or few non-correct assessments.

Comparing the results

Each observer assessed 48 images, giving a total of 1008 assessments. 30 non-correct assessments of a total of 1008 selections were identified and 23 of them were made by CVD observers as presented in Table 4.

Table 4: Assessment results in each group of observers.

	Correct	Non-correct	Total	Correctness
CVD	313	23	336	93.15 %
Normal	665	7	672	98.95 %
Total	978	30	1008	97.02 %

Comparing the results from the two groups with the Chi-square method give a P-value of 2.0E-7which is significant for $P<0.05$. There are significant differences between the CVD and color normal observers.

Further we compare the results for both groups of observers for each of the visual angles. As indicated by the P-values values significant for $P<0.05$from the Chi-square method in Table 5, there is a significant difference between the CVD and color normal observers, and that the difference increases as the visual angle is reduced. At last we compare variation of visual angles within each group. As the P-values values significant for $P<0.05$ in Table 6 and Table 7 illustrates, there is no significance of correlation.

Table 5: P-values significant for P<0.05 from the Chi-square method for the color size effect for CVD versus normal observer.

		Normal observer		
		Visual angle		
		3.5°	2.3°	1.2°
CVD	3.5°	0.11		
	2.1°		0.032	
	1.2°			6.3E-5

Table 6: P-values significant for P<0.05 from the Chi-square method for the color size effect for the CVD observers.

Visual angle for CVD observers			
	3.5°	2.3°	1.2°
3.5°		1	0.21
2.3°	1		0.21
1.2°	0.21	0.21	

Table 7: P-values significant for P<0.05 from the Chi-square method for the color size effect for the normal observers.

Visual angle for color normal observers			
	3.5°	2.3°	1.2°
3.5°		0.65	1
2.3°	0.65		0.65
1.2°	1	0.65	

Based on these results there is a significant difference between the groups, and that the difference increases as the visual angle is reduced. When the effect of visual angles is compared within each group, there is no significance of correlation.

Discussion

We have discovered that some distinct observers have problems with certain colors (Figure 6, images 2 and 5) and that some colors (Figure 5) are generally difficult for some CVD observers. Some of the errors are believed to be typo errors, especially when they appear as one of a kind in certain images. Also, one of the observers that was most distracted by the dropdown list was the one with most errors.

The experiment setup may be a cause of coincidence selections, as many of the observers reported that the selection were made on pure guess or based on patches close in the ordered legend. Further, the order of the colors in the legend could sometime give the answer away if the matching patch was above or under the possible confusing color. A possible solution to this could be to separate each of the four colors to each corner of the patch in order to increase the distance between them. But then the resemblance to a map legend would be lost.

Conclusion and future work

An experiment was conducted on colors selected from an official Norwegian map product and the test observers recruited among CVD and normal observers. The experiment revealed that the CVD observers made significant more errors than the normal observers, especially when the visual angle was reduced. Based on these results, some color combinations used in the color coding of a certain map are not distinguishable for CVD observers. Further, the experiment revealed that the ability to distinguish colors was more influenced by variation of visual angles for the CVD compared to the normal observers. This corresponds to earlier results by Paramai et al. [32] regarding color size effect and visual field, indicating that differences between CVD and normal observers are not significant when larger fields of view (≥3°).

This experiment was set up under a specific physical environment, so future work may include variation of light sources. Also, adding noise to the background (as different colors or textures) to investigate if the ability to discriminate colors is affected will make a great impact of the research of map making for color deficient observers.

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Appendix A: Color coding of map elements

Color	R	G	B	Object represented	Geographic representation
	247	190	140	City and built-up area	Area
	215	215	215	Industrial area	Area
	210	230	124	Land area, forest	Area
	255	247	163	Cultivation	Area
	255	255	230	Non forested land	Area
	155	185	60	Leisure, park, graveyard	Area
	155	185	60	Lake	Area
	210	35	42	Motorway	Line
	255	102	102	Motorway (tunnel)	Line
	110	110	110	Secondary road	Line
	200	200	200	Secondary road (tunnel)	Line
	195	30	40	Track, path	Line
	0	166	255	River	Line
	0	156	0	Border (nature conservation area)	Line
	190	90	190	Border (national)	Line
	180	135	255	Border (counties)	Line
	210	115	60	Border (baseline)	Line
	200	133	70	Contour	Line
	0	255	0	Accessible	Line
	0	204	0	Accessible	Line
	255	200	0	Fairly accessible	Line
	255	50	0	Not accessible	Line
	153	95	32	Dwelling	Point
	214	135	35	Leisure home	Point
	154	95	33	Farm, outhouse, garage	Point
	255	0	0	Cabin	Point
	90	135	222	Other trade building	Point