Displays 38 (2015) 44–49

Contents lists available at ScienceDirect

Displays

journal homepage: www.elsevier.com/locate/displa

Measurement of minimum angle of resolution (MAR) for the spatial grating consisting of lines of two colors

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ARTICLE INFO

Article history:
Received 22 October 2013
Received in revised form 27 February 2014
Accepted 27 February 2015
Available online 12 March 2015

Keywords:
Minimum angle of resolution (MAR)
Two alternative forced choice (2AFC)
Visual acuity
Grating

ABSTRACT

Minimum angle of resolution (MAR) was measured for the grating which consisted of lines of two colors selected from Red, Green, Blue, White and Black. Method of two alternative forced choice (2AFC) was used where the participants were asked to answer the direction of the color grating of the horizontal or vertical directions. From the measured psychometric function of the ratio of the correct answers, MAR which corresponded to the threshold of 75% correct answer ratio was determined. MAR of the grating patches with more than one primary color was measured to be affected by the combination of colors and to be 10–30% larger than that of the grating patch of White–Black. While the resolving power for Blue pattern had been known to be worse than those for Green and Red patterns, MAR of the grating including Blue was not always the worst.

1. Introduction

One pixel of display consists of the subpixels of the different colors. Various colors can be generated by the separate control of luminance of each subpixel in a pixel. Configuration of the subpixels of the different colors inside pixels determines the capability of the display to spatially generate the colored image information.

It had been known that people resolve the Blue patterns poorly compared with the Green or Red patterns. On retina inside human eyes, L-, M- and S-cone photoreceptors were distributed which respond preferentially to long-, middle- and short-wavelength light, respectively. The different resolving power of the colors was generally attributed to the different spatial distribution of L-, M- and S-cone [1–4]. And this phenomenon has been used in some of the display applications such that the subpixel configuration is not RGB stripe or the spatial distributions of the subpixel of Red, Green and Blue colors are not equal [5–8].

However, most of the photos or the images that people observe consist of the various colors and the images represented by one primary color are quite rare. Hence, the resolving power for the images consisting of multiple colors may show the trends different from those consisting of one primary color. In this respect, the minimum angle of resolution (MAR) was investigated using the grating patches consisting of the repeating two color lines.

Two alternative forced choice (2AFC) method was employed where patches of the grating of the horizontal or vertical directions were shown to the participant and each participant was asked to answer the line direction of each grating patch. The ratios of the correct answers were collected for the various color conditions and MAR were determined from the threshold condition of the correct answer ratio of 75%.

2. Experiment

To measure the minimum angle of resolution (MAR) and the visual acuity, the grating patch of black and white lines had been used to determine whether the participant could discern the direction of the grating [9,10]. To measure MAR for the various combination of colors, an experiment was designed using the grating with two colors.

Two alternative forced choice (2AFC) method was used to determine whether the participant could discern the direction of the grating [11]. As a patch for the experiment, the grating with the vertical or horizontal directions was used and the participant was asked to answer whether the direction of the grating are vertical or horizontal. Fig. 1(a) illustrates the grating patch where two color lines of the same thickness of the vertical or horizontal directions were repeatedly placed. When the people can discern the grating lines, the ratio of correct answer will approach the

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http://dx.doi.org/10.1016/j.displa.2015.02.002
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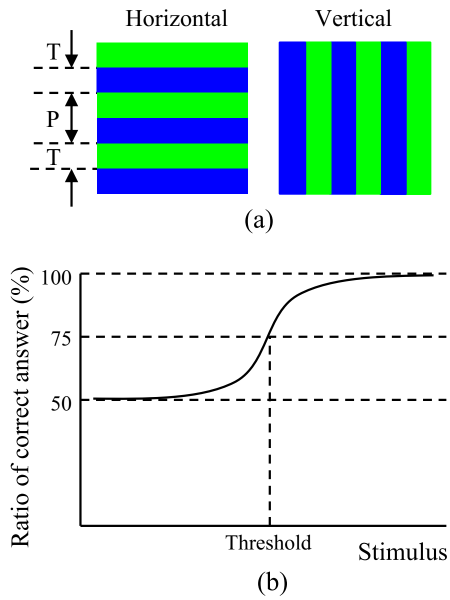


Fig. 1. Determination of minimum angle of resolution (MAR) by the two alternative forced choice (2AFC) method. (a) Two directions of grating patch of period *P* which consists of the repeated two color lines of thickness *T*. (b) The psychometric function for 2AFC method. Horizontal and vertical axes represent the stimulus and the ratio of the correct answers, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

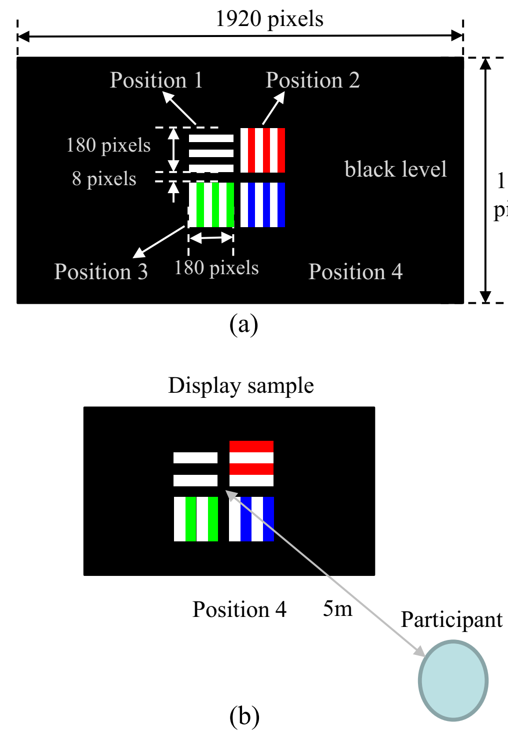


Fig. 2. (a) Schematic outline of input signal example where 4 grating patches of horizontal, vertical, vertical and verticals directions are located on the positions 1, 2, 3 and 4. The height and width of the active area of the sample display are 1080 and 1920 pixels where the pixel size of the sample display is 0.18 mm. Size of each grating patch is 180 pixels by 180 pixels, that is, 32.4 mm by 32.4 mm. (b) Schematic setup of the experiment. Input signal with 4 gratings patches of the horizontal or vertical directions was shown on the sample display. Illumination was 300 lux and the observation distance was 5 m.

asymptotic value of 100%. When the participant cannot discern the grating lines, the participant will guess the grating direction and the ratio of correct answer will approach the asymptotic value of 50%. Hence, in this experiment based on 2AFC method, the threshold that the participant can discern the grating should be (100 + 50)/2% = 75%. The typical psychometric function obtained from the experiment based on 2AFC method is illustrated in Fig. 1(b).

While the grating of the luminance profile of the sine wave was generally used for the measurement of MAR, the luminance profile of the input signal of Fig. 1(a) was the shape of the square wave. Yet, it was reported that the result obtained from the grating of the luminance profile of the square wave was equivalent to that obtained from the grating of the luminance profile of the sine wave [12]. Hence, the color grating of the luminance profile of the square wave of Fig. 1(a) was be used for the experiment. If MAR is not dependent on the colors, MAR will be the same irrespective of the colors of the grating.

For the measurement, the input signal consisting of 4 grating patches of the vertical or horizontal directions was used as illustrated in Fig. 2(a). The visual acuity was reported to be affected by the patterns around the optotype [13]. Therefore, this input signal consisting of 4 grating may provide the different result from that using only one grating. But in the observation of the images of photos or scenery, multiple color patterns exist inside one image. Hence, input signal of 4 grating patches were selected to investigate MAR on the case that multiple colors patterns were observed simultaneously.

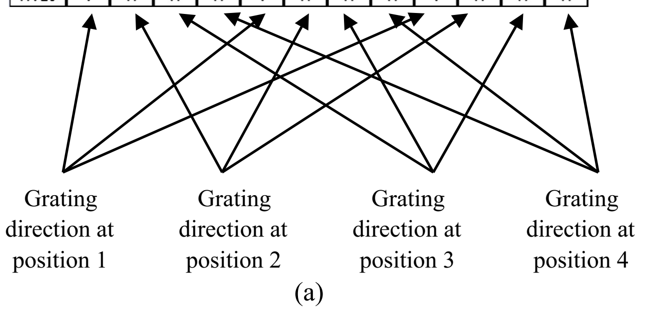
These 4 grating patch were placed near the center of the sample display as illustrated in an example of input signal of Fig. 2(a). Other area on the sample display was set at black level. Display of the diagonal size of 15.6 in., pixel pitch of 0.18 mm, pixel numbers of 1920 × 1080 and the color gamut of 62% with respect to NTSC was used as the display sample. The width and the height of the grating patch of Fig. 2(a) were selected to be 180 pixels and the gratings patches were separated by the distance of 8 pixels.

Fig. 2(b) illustrates the schematic setup of the experiment. Observation distance between the participant and the screen was selected as 5 m. Head of the participant was located such that eyes of the participant were on the line that passed through the center of the display sample. Illuminance of the experimental room was measured to be 300 lux by illuminance meter (LX-101, Lutron) and kept constant during the experiment.

When the horizontal and the vertical directions for 4 grating patches were used for equal number of times, 16 combinations of directions were possible for each input signal as illustrated in Fig. 3(a). Two colors of each grating were selected among White (W), Black (K), Red (R), Green (G) and Blue (B). And the lines of these two colors were repeated with the same spatial period in the grating patch. Selected colors were categorized into 3 groups, by the inclusion of White or Black. First color group consisted of White and one of other colors. Second color group consisted of Black and one of other colors. Third group consisted of combinations of the primary colors. For each color groups, 16 input signals were prepared as illustrated in Fig. 3(a). Hence, 48 input signals and 192 patches were prepared for each condition of the same line thickness. Grating of White–Black was always placed inside all the input signals as reference. Fig. 3(b) illustrates an example of input signal image of pattern type HV02 and color group 1.

To measure the luminance of the colors on the sample display, luminance meter (Spyder 4.0 Elite) was used [14]. Measured luminance and color coordinates for White (W), Black (K), Red (R), Green (G) and Blue (B) were illustrated in Fig. 4. The luminance of the black level was measured to be 0.617 cd/m^2. Sum of the measured luminance of Green, Red and Blue was equal to the measured luminance of White.

pattern	color group 1				color group 2				color group 3			
type	K W	R W	G W	B W	K W	R K	G K	B K	K	R G	R B	G B
HV01	V	V	H	H	V	V	H	H	V	V	H	H
HV02	H	H	V	V	H	H	V	V	H	H	V	V
HV03	V	V	V	H	V	V	V	H	V	V	V	H
HV04	V	V	H	V	V	V	H	V	V	V	H	V
HV05	H	H	H	H	H	H	H	H	H	H	H	H
HV06	V	H	V	V	V	H	V	V	V	H	V	V
HV07	V	H	V	H	V	H	V	H	V	H	V	H
HV08	H	V	V	V	H	V	V	V	H	V	V	V
HV09	V	H	H	V	V	H	H	V	V	H	H	V
HV10	H	V	V	H	H	V	V	H	H	V	V	H
HV11	H	H	H	V	H	H	H	V	H	H	H	V
HV12	H	H	V	H	H	H	V	H	H	H	V	H
HV13	V	V	V	V	V	V	V	V	V	V	V	V
HV14	H	V	H	H	H	V	H	H	H	V	H	H
HV15	H	V	H	V	H	V	H	V	H	V	H	V
HV16	V	H	H	H	V	H	H	H	V	H	H	H



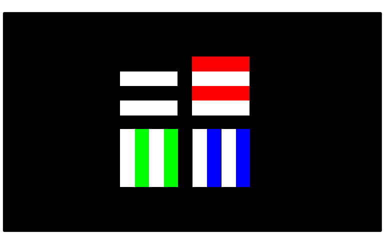


Fig. 3. (a) List of the color combinations and the directions of four grating patches used for the input signal. *H* and *V* represent the horizontal and vertical directions of the grating patches in four positions of each input signal. K, W, R, G and B represent Black, White, Red, Green and Blue. (b) An example of input signal image of pattern type HV02 and color group 1. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Line thickness of the grating was selected as 0.9 mm, 1.08 mm 1.26 mm such that the participant was difficult to discern the White–Black grating of $T = 0.9$ mm and could easily discern the White–Black grating patch of $T = 1.26$ mm on the observation distance. Generally 2 s had been reported to be given to the participant for this type of experiment using the grating patch [15,16]. As there were 4 grating patches on each input signal, the duration of 8 s was selected. During experiment, each input signal from one of 3 color groups of Fig. 3 was displayed for 8 s. Every time the input signal was changed, a beep sound was made to notify the change of the input signal to the participant. After 4 s, the other beep sound was given to notify that 4 s passed. Within 8 s, each participant was asked to answer whether the each direction of four gratings patches were horizontal or vertical. All participants answered within the given 8 s without the shortage of the time. Measurement for one color groups took about 128 s as one color group consisted of 16 input signals. After 16 input signals of one color group were displayed, the resting time of 3 min was provided and experiment was continued and the input signals from other color groups were displayed. Total measurement for 3 color groups took about 12 min. The participant can become tired or lose interest near the end of the experiment and this can affect the result.

	x	y	luminance Y
White	0.308	0.337	275.617
Black	0.308	0.292	0.617
Red	0.614	0.367	67.737
Green	0.32	0.632	161.304
Blue	0.15	0.123	47.133

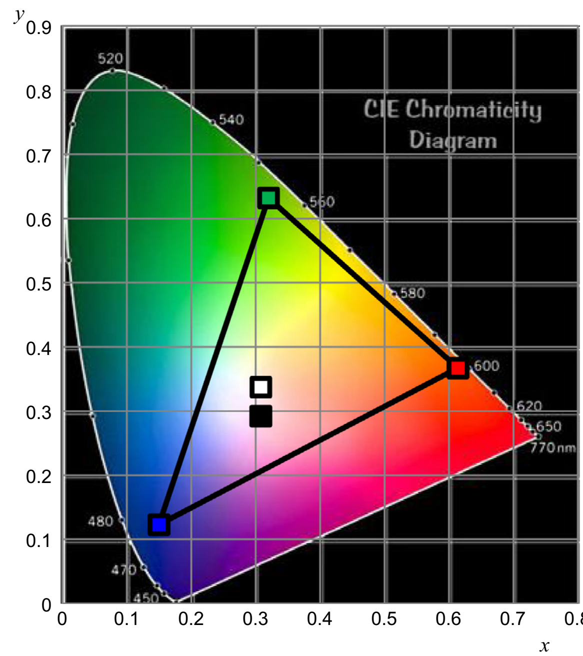


Fig. 4. Luminance of the display sample measured at the input signal of the uniform screen of White, Black, Red, Green and Blue, respectively. The horizontal and vertical axes represent *x* and *y* which is the color coordinates in CIE1931 color space. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Hence, 3 sequences were designed where the order of color groups 1, 2 and 3 were interchanged as illustrated in Fig. 5. For each participant, each sequence was measured per day. In case of White–Black combination, the grating patches of the same line thickness were shown 144 times to each participant. In case of other combinations of KWRGB, each combination was shown 48 times to each participant.

Four participants with the visual acuity of 1.2 in decimal notation were selected. They were in their twenties and three of them wore the corrected eyeglasses as listed in Table 1. Visual acuity of 1.0 in decimal notation corresponds to the ability to discern the interval of 1.5 mm at the distance of 5 m. Before the experiment started, each participant was explained about the purpose of the

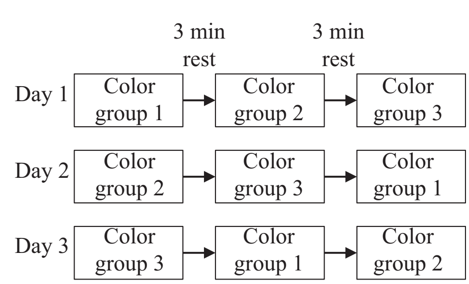


Fig. 5. Measurement procedure which consists of 3 sequences and takes 3 day for each participant. For each color groups, 16 input signals were prepared.

Table 1
Ages and visual acuity of four participants.

Participant	Age	Visual acuity
A	23	1.2 (uncorrected)
B	25	1.2 (corrected by glasses)
C	26	1.2 (corrected by glasses)
D	28	1.2 (corrected by glasses)

experiment and the correct verbal response during the experiment such that the participant must answer the direction of the grating patch even when the participant could not discern the grating patch. Input signals described in Fig. 3(a) and Table 1 were shown to the participants and from the answers of the participants, the ratio of the correct answers were collected for the grating patches at the different lines colors and line thickness.

3. Results and analysis

Fig. 6 illustrates the measured ratio of the correct answers obtained from four participants. The ratio of the correct answers were measured to be different for the various combinations of the two color lines. That means that MAR were affected by the colors of the observed images. The ratio of the correct answers for grating line thickness of 0.9 mm was measured to be the highest for White–Black grating. It means the participants could discern the White–Black grating better than the gratings of other colors.

To represent the result of Fig. 6 quantitatively for the gratings of other color combinations, the line thickness corresponding to the correct answer ratio of 75% threshold needs be estimated. To fit the psychometric function of 2AFC illustrated in Fig. 1(b), Formula (1) was proposed [17].

$$S(x) = 50\% + \frac{50\%}{1 + e^{-ax+b}} \quad (1)$$

This function approaches 50% and 100% as x approaches $\pm\infty$ as illustrated in Fig. 7(a). In Formula (1), $S(x)$ becomes 75% when x is b/a. From the measurement conditions, the line thickness of 0.9 mm, 1.08 mm and 1.26 mm provided three data points which could be used to determine the constant a and b. If the ratio of the correct answers approaches the asymptotic line of 50% or 100%, small change of the ratio can result in the large change of x. The data below 55% or above 95% were more prone to errors

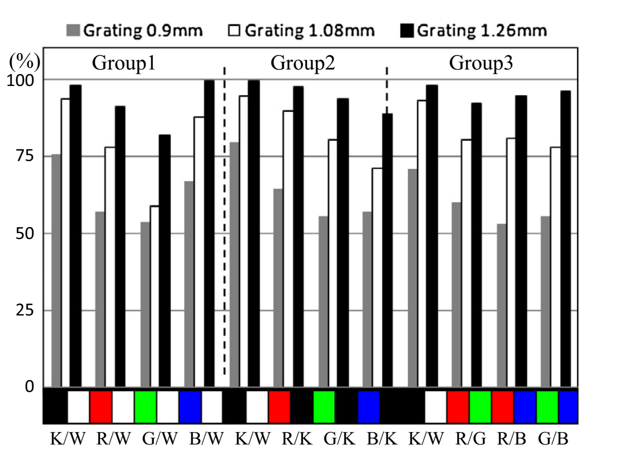


Fig. 6. The measured ratio of the correct answers for the colored grating patches. Horizontal axis represents the conditions of two color combinations for the grating patches listed in Fig. 3. Vertical axis represents the ratio of the correct answers. Numbers on the upper side represent the line thickness of the grating. Groups 1, 2, 3 represent the color group defined in Fig. 3. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

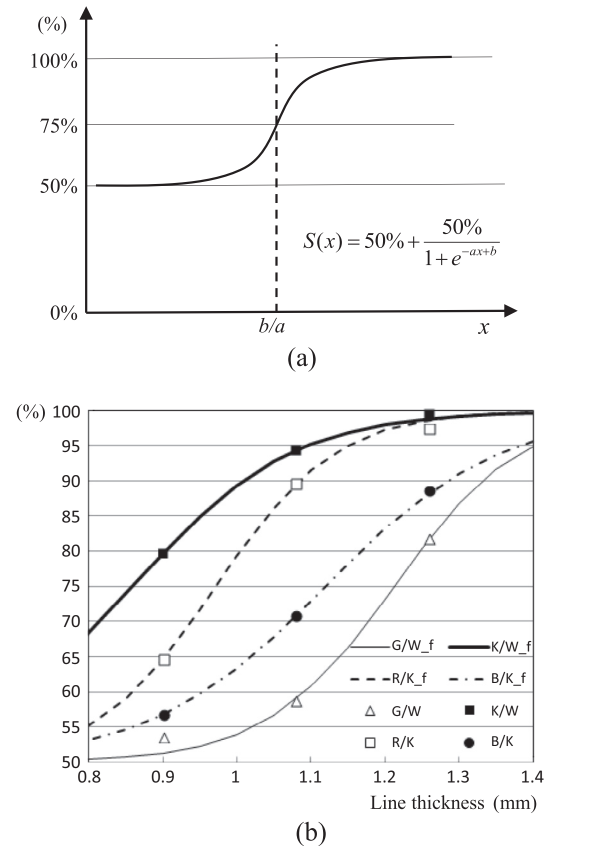


Fig. 7. (a) Function $S(x)$ with asymptotic line of 50% and 100% which is used to fit the psychometric function. (b) Estimation of 75% ratio using the function $S(x)$ and the measured data of the line thickness and correct answer ratio. Horizontal and vertical axes represent the line thickness and the ratio of the correct answer, respectively. Color combinations of the grating patches are listed in the lower right side where '_f' represents the fitted curve.

and the estimation of line thickness at the correct answer ratio of 75% was important. Hence if one of data of the correct answers was near 50% or 100%, only two line thickness near the correct answer ratio of 75% were used to determine a and b values. Fig. 7(b) illustrates the fitted curve of the function $S(x)$ derived from the two points among 3 measured point. In Fig. 7(b), function $S(x)$ did not match the position of 3 data points simultaneously for the result of R/K and G/W, as one of the measured result were below 55% or above 95%.

Fig. 8 illustrate the minimum angle of resolution (MAR) corresponding for the correct answer ratio of 75% derived using Formula (1) and the result of Fig. 6. The largest MAR was observed for the grating of Green–White (G/W) while the smallest MAR was observed for the grating of White–Black (K/W). The smaller MAR is, the eye can discern the grating patch of smaller line thickness. When one color of the gratings was White, MAR of the participants was measured to be in the order of K/W < B/W < R/W < G/W. The result showed that participants could discern K/W grating whose period was 30% smaller than that of G/W. When one color of the gratings was Black (K), MAR was measured to be K/W < R/K < G/K < B/K. When colors of the gratings consisted of RGB, the grating period that the participant could discern was measured to be R/G < R/B < G/B.

It had been known that people could resolve Green or Red patterns better than Blue patterns [1–4]. Measured results of MAR for the color gratings of B/K (Blue–Black), G/K (Green–Black), R/K (Red–Black) were in accord with this. Yet, in case that Blue was observed with other colors except Black, MAR for the color grating

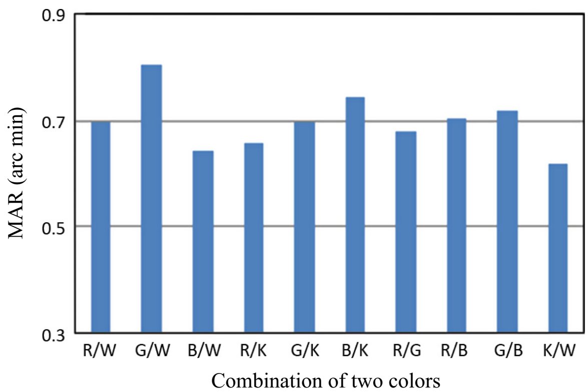


Fig. 8. Minimum angle of resolution (MAR) derived from the psychometric function of each colored grating patches at the correct answer ratio of 75%. The vertical and horizontal axes represent MAR in arc min and the condition of two color combination for the grating patches. RGBWK represent Red, Green, Blue, White and Black, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

which included Blue was measured to be not always the worst. For example, the participant could discern the grating of B/W (Blue–White) better than the grating of G/W (Green–White) or R/W (Red–White). MAR for the grating patch of B/W (Blue–White) was almost equivalent to that of W/K (White–Black). It means that in the observation of color images, the ability to discern the detailed pattern was not solely determined by one color but affected by the other colors.

Visual acuity or MAR were known to be affected by various factors such as the pupil size, the luminance contrast, the characteristics of photo-receptors and the chromatic aberrations.

The pupil size of the observer was known to affect MAR such that the change toward the larger pupil size resulted in the larger MAR [10]. Though the luminance of the grating patch was different for the various color combination, the area of each grating patch only occupied the angular range of 0.37° from the field of view and the active area of the sample display was kept constantly at the black level except the area of grating patches as illustrated in Fig. 2. The illuminance of the room for the experiment was kept constant as 300 lux. Hence, among the lights incident on the eyes, the amount of ambient light would be much larger than the amount of light coming from the grating patch irrespective of the color of the grating. As the pupil size was determined by the illuminance which was kept constant during the experiment, it was concluded that the measured result of different MAR was not caused by the change of the pupil size.

Luminance contrast of the grayscale input signal was known to affect the minimum angle of resolution such that the lower contrast result in the lower MAR [11]. Luminance contrast can be defined as Formula (2).

$$\text{Luminance contrast} = \frac{L_1 - L_2}{L_1 + L_2} \tag{2}$$

Here L_1 and L_2 represent the luminances.

The measured luminance of colors of Fig. 4 were used as L_1 and L_2 of Formula (2). And the luminance contrast was derived as in Table 2. In Table 2, the ratio of MAR of color grating patch with respect to MAR of the grating patch of White–Black were shown as well.

In case of the grating patches of W/K, R/K, G/K, B/K where one color of the grating patches was Black, the luminance contrast for these combinations were almost equal to 1. And the gratings for these combinations could be treated as the equal luminance contrast. MAR of R/K, G/K, B/K grating patches increased 7%, 13%, 20% respectively compared with MAR of W/K grating patches. L-, M- and S-cone photoreceptors on the retina respond preferentially to long-, middle- and short-wavelength light, respectively. In case of W/K grating patches, all of L-, M- and S-cone photoreceptors can be stimulated by the white light. However, In case of R/K, G/K, B/K grating patches, light of Red, Green and Blue will stimulate some of photoreceptors less effectively. Hence the resolving power decreases and MAR increases. The difference of MAR for R/K, G/K, B/K may be attributed to the different spatial distribution and the different spectral response of L-, M- and S-cone photoreceptors [1–4].

Table 2
Increase of MAR with respect to that of White–Black (W/K) and the luminance contrast for the grating of the various color combinations. K, W, R, G and B represent Black, White, Red, Green and Blue.

Colors of grating	MAR increase (%)	Luminance contrast
R/W	13	0.61
G/W	30	0.26
B/W	4	0.71
R/K	7	0.98
G/K	13	0.99
B/K	20	0.97
R/G	10	0.41
R/B	14	0.18
G/B	16	0.55

In case of the grating patches of R/W, G/W, B/W, luminance contrast for G/W was smaller than those of B/W and R/W. Increase of MAR for grating of G/W may be attributed to these difference of luminance contrast.

4. Conclusion

MAR (minimum angle of resolution) was measured from the grating patches of two colors which included Black, White, Red, Green and Blue. Compared with MAR of the grating patches of W/K (White–Black) lines, MAR of the gratings patches of other color combinations were measured to be larger.

While MAR of Blue patterns was known to be worse than that of Red or Green patterns, MAR measured from the grating patches including Blue was worse only for the combination of B/K (Blue–Black). In case that Blue was combined with White, measured MAR for the grating patch of B/W (Blue–White) was almost equivalent to that of W/K (White–Black).

Result of measured MAR for the colored grating could be affected by the combined effects of the various factors such as the characteristics of photo-receptors, luminance contrast. In the observation of photos or realistic images, MAR would depend on the combined contributions of these factors. The result of MAR at the various color combinations showed that in the observation of color images, the ability to discern the detailed pattern was not solely determined by one color but affected by the other colors.

In the display, the configuration of the subpixels of the different colors determines the capability of the spatial distribution of colored images by the display. If the spatial distributions of the subpixels of the different colors are designed to be unequal, MAR for the various color combination had better be considered in design such that the viewer cannot discern the non-equality of the spatial distribution of subpixels.

Acknowledgement

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2013R1A1A2005812).

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