Colorblind-friendly Halftoning

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***Abstract*— Most images are natural images and most of them are still delivered in printed form nowadays. Halftoning is a critical process for printing natural color images. However, conventional colorblind aids do not make use of the halftoning process directly to produce colorblind-friendly image prints. In this paper, a halftoning algorithm is proposed to reduce the color distortion of an image print in the view of a colorblind person and embed hints in the image print for a colorblind person to distinguish the confusing colors. To people with normal vision, the color halftone looks the same as the original image when it is viewed at a reasonable distance, which is not achievable when conventional techniques such as recoloring and pattern overlaying are used to produce a color print for the colorblind. Besides, no dedicated hardware is required to view the printed image.**

Keywords—colorblind, color vision deficiency, halftoning, colorblind-friendly hardcopy, color separation

I. Introduction

Color blindness, also known as color vision deficiency (CVD), is a medical condition that affects approximately 200 million people globally [1]. Due to either damages or flaws in their visual nerve system, people with CVD cannot discriminate colors effectively. Various colorblind aids have been developed to assist them in distinguishing colors. In general, these aids were developed based on the following techniques: (1) substitute the colors that are confusing to colorblind people with some other colors to enhance color contrast [2-5]; (2) overlay visual patterns on top of the confusing colors to make them distinguishable [6-9]; and (3) utilize the optical parallax effect between two eyes to create binocular disparity for one to distinguish regions of different colors [10].

Although these techniques help to improve the situations, there remain limitations. First, recoloring cannot resolve color ambiguities when an image contains many colors as the number of distinguishable perceived colors are very limited to colorblind people. Accordingly, it is difficult to handle natural images with rich color. Second, adding patterns or changing colors damages the original content of an image and hence the processed image provides misleading information to people with normal color vision. Two separate versions are needed for different groups to interpret. Third, dedicated visual aids are required for real-time interpretation.

Though mobile devices are popular nowadays, tremendous amount of images are still delivered in printed form and viewed on paper. Halftoning is a critical process to make a color image printable with most printers [11]. It involves color quantization and hence a printed image unavoidably contains noise, but the noise can be invisible if it is carefully controlled [12,13]. However, none of the current processing methods used in a colorblind aid take this factor into account and make use of it to embed useful information into a printed image for people with CVD to resolve color confusion.

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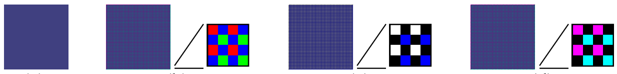
In this paper, we propose taking advantages from halftoning to produce colorblind-friendly image prints. It is a breakthrough to tackle the problem in this way. While conventional processing methods sacrifice original image content to make a printed image colorblind-friendly, the proposed approach makes use of a side effect of the unavoidable halftoning step to achieve the same goal. Besides, unlike the regular patterns used in conventional pattern superimposition methods, the stochastic noise patterns introduced by halftoning are much less visible at the same distance.

II. Motivation

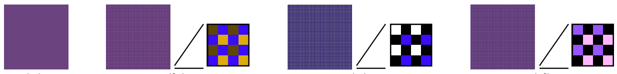
There are three kinds of retinal photoreceptors called L, M and S cone cells in a human's visual nerve system. In case a particular type of cone cells are missing or do not function at all, the affected individuals are called *dichromat*. They are classified as *protanope*, *deuteranope*, and *tritanope* respectively when the type of problematic photoreceptors is L, M, and S. People having problems with their L or M cone cells are difficult to distinguish between red and green. These cases of CVD are collectively known as red-green CVD and they cover over 99.9% of all cases of CVD [14]. In this study, we put our focus on this group of colorblind people.

Most printers nowadays use four inks to produce image copies and hence only red(R), green(G), blue(B), white(W), cyan(C), magenta(M), yellow(Y) and black(K) can be used to render a color image. Any other colors are actually simulated by spatially mixing dots of these eight primary colors. The mixing is not unique and it affects how a printed image looks to colorblind people. Figure 1 shows an example in which a constant color patch is produced by mixing primary color dots in three different ways. When the produced halftones are viewed from a reasonable distance, they look identical to each other. (If they look different to you, it may be due to the problem of your printer. Please read all simulations results from the PDF file directly. Halftones are sensitive to resampling and hence please make sure that your PDF file is displayed on scale to avoid aliasing.) However, from a deuteranope's point of view, they are different. Figure 2 shows the simulated views of a deuteranope. Like all other simulation results presented in the paper, they are derived based on Machado et al.'s distortion model with severity=1 [15]. One can see that the mixing scheme shown in Fig. 2(c) introduces less distortion to the perception of a deuteranope. In fact, it is understandable because this mixing scheme only



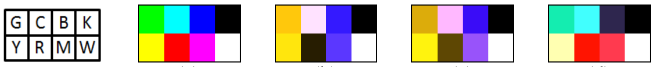
(a) (b) (c) (d)

Fig. 1 The halftone of a constant color patch can be produced by mixing primary color dots in different ways. (a) constant color patch whose color is (1/4,1/4,1/2) in (r,g,b) format, where $r,g,b \in [0,1]$; (b) halftone obtained by mixing R, G and B dots; (c) halftone obtained by mixing W, K and B dots; and (d) halftone obtained by mixing C, M and K dots.



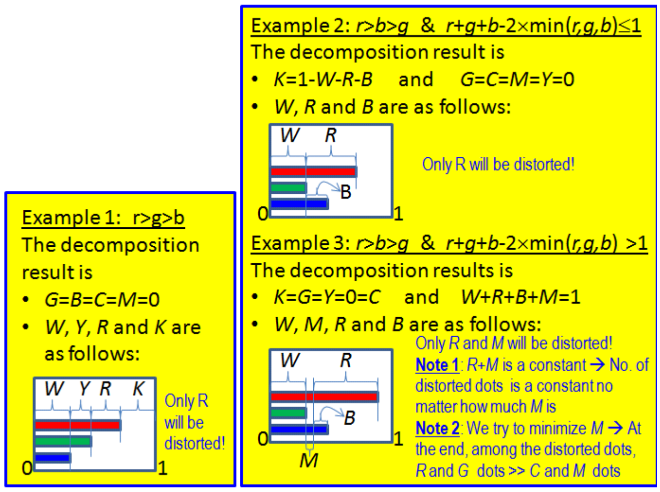
(a) (b) (c) (d)

Fig. 2 (a), (b), (c) and (d) are, respectively, how Figs. 1(a), (b), (c) and (d) look to a deuteranope. They are simulated based on Machado et al.'s distortion model [15].



(a) (b) (c) (d)

Fig. 3 The 8 primary colors supported by a CMYK printer and how they look to different people. (a) people with normal vision, (b) protanope, (c) deuteranope and (d) tritanope. The views shown in (b)-(d) are simulated based on Machado et al.'s distortion model [15].



(a) (b)

Fig. 4 Examples that show the design philosophy of the proposed color separation scheme for different situations: (a) $b = \min(r,g,b)$ and (b) $b \neq \min(r,g,b)$.

uses black, white and blue color dots. A deuteranope has no problem to percept the color of these color dots.

It is possible to explicitly control the mixing ratio of the primary colors in a local region. For examples, HED [16] and Fung and Chan's algorithm [17] decompose the color image into eight different channels, estimate the dot budgets for individual primary colors that should appear in the halftoning output, and position the color dots in the output accordingly. Conventional channel decomposition (a.k.a. color separation) schemes [16,17] try to minimize the brightness variation among adjacent color dots. It helps to improve the visual quality of the resultant color halftone.

Figure 3 shows how the eight primary colors are distorted in the perception of dichromats. One can see that colors R, G, C and M are seriously distorted in the perception of protanopes and deuteranopes. In view of this fact, we should minimize the number of these problematic color dots in a halftoning output.

The noise characteristics of a halftone can be tuned by adjusting the average cluster size in the halftone [12]. As long as it is controlled properly, the noise is invisible when the halftone is viewed at a reasonable distance [18]. By taking these factors into account, the proposed halftoning algorithm is composed of a color separation stage and a dot positioning stage. In the former stage, it minimizes the problematic color components used in mixing a pixel color. In the latter stage, it modulates the local noise characteristics of the halftone.

III. Colorblind Friendly Color Separation

In our proposed color separation (CS) scheme, a color image is purposely decomposed into eight monochrome contones, one for each Neugebauer primary (i.e. R, G, B, C, M, Y, K and W), to avoid dot overlapping in the color halftone to be produced and minimize the use of R, G, C and M dots. Without dot overlapping, the number of problematic color dots in the resultant color halftone determines the percentage of the potential affected area in the halftone. In the proposed CS process, the color of each pixel is converted to an 8-element vector in format (W,K,R,G,B,C,M,Y), where W, K, R, G, B, C, M and Y are, respectively, the intensity values in the W, K, R, G, B, C, M and Y channels. To guarantee that there is no dot-on-dot printing at the end, the conversion is realized under the following constraint.

$$W+K+R+G+B+C+M+Y=1 \quad (1)$$

Without loss of generality, we assume that the pixel color of the input color image is in (r,g,b) format, where $r,g,b \in [0,1]$. Blue is a safe color to protanopes and deuteranopes. Accordingly, in our CS scheme, we handle the following two cases separately to produce the conversion result.

<u>Case 1</u>: $b = \min(r,g,b)$

$$W = b; \quad Y = \min(r,g) - b;$$
$$R = \max(r-g,0); \quad G = \max(g-r,0);$$
$$K = 1-\max(r,g,b); \quad B = C = M = 0 \quad (2)$$

<u>Case 2</u>: $b \neq \min(r,g,b)$

(a) <u>Subcase 2a</u>: $r+g+b-2\times\min(r,g,b) \leq 1$

$$W = \min(r,g,b); \quad B = b - W;$$
$$R = \max(r-W,0); \quad G = \max(g-W,0);$$
$$K = 1-\max(r,g) - B; \quad C = M = Y = 0 \quad (3)$$

(b) <u>Subcase 2b</u>: $r+g+b-2\times\min(r,g,b) > 1$

$$W = \min(r,g,b);$$
$$M = \begin{cases} r+g+b-2W-1 & \text{if } g < r \\ 0 & \text{else} \end{cases};$$
$$C = \begin{cases} 0 & \text{if } g < r \\ r+g+b-2W-1 & \text{else} \end{cases};$$
$$B = b-W-C-M; \quad R = \max(r-W-C-M,0);$$
$$G = \max(g-W-C-M,0); \quad K = Y = 0 \quad (4)$$

Figure 4 shows the design philosophy of the proposed color separation scheme with three examples, one for each case. In all cases, we minimize R and G by first combining r, g and b to W. Figure 4(a) shows an example of case 1 in which we have $r>g>b$. In this example case, we maximize W by combining r, g and b as much as possible and then maximize K by combining r and g as much as possible to Y. By so doing, R is minimized after maximizing W, K and Y. As shown in Fig.3, the distortion to Y is visually less significant

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than the distortion to R, G, C and M in a dichromat's view. Hence, we minimize R under the premise that the sum of R and Y is minimized.

Examples 2 and 3 in Fig. 4(b) show, respectively, subcases 2a and 2b under condition $r>b>g$. In the case of Example 2, after combining r, g and b to maximize W, we do not further combine b and r to produce M because doing so does not change the sum of $M+R$. It cannot reduce the percentage of the problematic color components in the pixel. In such a case, we minimize M to maximize R such that the overall distortion in protanopes' and deuteranopes' perception is mainly contributed by the distortion in red. We believe that it would be easier to handle the distortion if its sources are purer.

In the case of Example 3, we have $r+g+b-2\times\min(r,g,b)>1$. After combining r, g and b to maximize W, we have to combine b and r to some extent to make $W+R+B+M=1$. Otherwise, it is impossible to satisfy constraint (1). In other words, we try to achieve the same goal as in subcase 2a under constraint (1).

After color separation, the intensity value of each color component of a pixel plays a role to determine the number of the corresponding Neugebauer primary color dots in the final color halftone. Specifically, we have

$$N_P = round\left(\sum_{i,j} P(i,j)\right) \text{ for } P \in \{R, G, B, C, M, Y, W, K\} \quad (5)$$

where $P(i,j)$ is the intensity value of color component P of pixel (i,j), and N_P is the total number of dots in color P in the color halftone.

In short, the objectives of the proposed CS scheme are to minimize (1) $N_R+N_G+N_C+N_M$ and (2) $(N_C+N_M)/(N_R+N_G)$ under the constraint $\Sigma_P P(i,j)=1$ for all pixel (i,j). It effectively reduces the distortion in protanopes' and deuteranopes' perception by minimizing the number of distorted dots, and it makes the color shift in red and green dots be the major contribution to the overall distortion. For reference purpose, the conversion result of pixel (i,j) is referred to as $I_c(i,j)$ hereafter.

IV. Noise Characteristics Modulation

The proposed halftoning algorithm is a low-complexity algorithm based on the error diffusion technique [19]. Two diffusion filters are used during the error diffusion process to modulate the local noise characteristics of the color halftone. The modulation is achieved by adjusting the average dot cluster size in a specific local region based on the potential of being distorted in the region.

In its realization, the extent of the potential color distortion in the perception of colorblind people at pixel (i,j) is measured as $R_{pd}(i,j) = (R(i,j)+G(i,j)+C(i,j)+M(i,j))/\Sigma_P P(i,j)$. The proposed dot positioning scheme processes the image pixel by pixel in a serpentine order.

Suppose the pixel being processed is pixel (i,j). After quantizing its color to the Neugebauer primary color that has the maximum intensity values in $I_c(i,j)$, the quantization error in each color channel is diffused with a diffusion filter to update I_c as follows.

$$P(i+x,j+y) = P(i+x,j+y) + E_p(i,j)F(x,y) \quad \text{for } (x,y)\in\Omega \quad (6)$$

where $F(x,y)$ is the $(x,y)^{th}$ coefficient of an error diffusion filter, Ω is the support of the diffusion filter, $P(i+x,j+y)$ is the $(i+x,j+y)^{th}$ pixel in channel P and $E_p(i,j)$ is the quantization error of pixel (i,j) in channel P. In particular, we have

$$E_p(i,j) = \begin{cases} P(i,j)-1 & \text{if } P \text{ is the output color of the quantization} \\ P(i,j) & \text{else} \end{cases} \quad \text{for } P\in\{R,G,B,C,M,Y,W,K\} \quad (7)$$

Two diffusion filters defined as

$$F_1 = \frac{1}{16}\begin{bmatrix} 0 & * & 7 \\ 3 & 5 & 1 \end{bmatrix} \quad (8)$$

and

$$F_2 = \frac{1}{64}\begin{bmatrix} 0 & 0 & * & 0 & 6 & 4 \\ 1 & 6 & 0 & 0 & 5 & 3 \\ 0 & 4 & 7 & 3 & 5 & 3 \\ 0 & 3 & 5 & 3 & 4 & 2 \end{bmatrix} \quad (9)$$

are used to adjust the average cluster size in the local region of pixel (i,j) based on $R_{pd}(i,j)$. In eqns. (8) and (9), * marks the position of the $(0,0)^{th}$ coefficient of a filter. The two filters were proposed in [19] and [20] separately for producing dots and clusters respectively in a halftone with the error diffusion technique.

When $R_{pd}(i,j)>0.2$, pixel (i,j) is confirmed to be in a problematic color region in which distortion is likely visible. Diffusion filter F_2 is then used to generate clusters. When $R_{pd}(i,j)=0$, pixel (i,j) is considered to be in a clean region without visible distortion. Diffusion filter F_1 is then used to generate dots. When $0\le R_{pd}(i,j)\le 0.2$, the content in the region is rendered with both dots and clusters with a mixing ratio equals to $(1-5R_{pd}(i,j)):5R_{pd}(i,j)$. The mixing is achieved by picking one of the two filters based on a real-time test. Filter F_2 will be used if $R_{pd}(i,j)>v$, where v is a randomly generated value which is uniformly distributed over the range of [0, 0.2], or else Filter F_1 will be used. This arrangement introduces a transition region such that the noise characteristics can smoothly change from a problematic region to a clean region.

After processing pixel (i,j) and updating its neighbors by diffusing the quantization error of pixel (i,j), the dot positioning scheme continues to process the next pixel until all pixels are processed. The final output is an 8-color halftone. The dot positioning scheme proposed in this section is referred to as DPwNCM hereafter.

V. Simulation Results

Simulations were carried out to study to what extent the proposed method can help colorblind people. The first study is on evaluating the impact of the proposed color separation scheme. Figure 5 shows two color halftones and how they look to colorblind people. Both halftones were obtained with the same error diffusion-based dot positioning scheme but adopted different CS schemes. The used dot positioning scheme is almost identical to DPwNCM except that it uses a fixed diffusion filter (F_1) to diffuse the quantization error whatever the value of $R_{pd}(i,j)$ is. In other words, no noise characteristics modulation is applied. For reference purpose, this dot positioning scheme is referred to as DPw/oNCM. To normal people, the halftones shown in Figs. 5(a)(i) and 5(b)(i) look the same. However, to protanopes and deuteranopes, Fig. 5(a)(i) is less distorted than Fig. 5(b)(i). The background

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region in Fig. 5(a)(iii) is much closer to the original than that in Fig. 5(b)(iii). In fact, 67.35% of the pixels in Fig. 5(b)(i) are either R, G, C or M dots while there are only 13.2% in Fig. 5(a)(i). One can see that the whole image is biased to magenta in Fig. 5(b)(iii) while it is not the case in Fig. 5(a)(iii). The proposed CS scheme can effectively minimize the problematic color dots in a color halftone and, accordingly, reduce the color distortion in a protanope's or deuteranope's view at no penalty to people with normal sight.

The second study is on evaluating the overall performance of our proposed colorblind-friendly halftoning algorithm. After minimizing the energy in channels R, G, C and M with our proposed CS scheme, DPwNCM is exploited to produce color halftones. Figure 6 shows how the proposed algorithm can provide hints to help protanopes and deuteranopes to distinguish the confusing colors in a colorblind test chart.

Figure 7 shows how the output of the algorithm looks to normal people and colorblind people at different distances. Note that viewing an image that is printed at half DPI is equivalent to viewing the original at half distance or enlarging the image by 400%. We can distinguish distorted regions and clean regions based on their noise characteristics when we get close enough to a printout or magnify a printout large enough.

Table 1 shows the quality performances of the halftones produced with two different approaches. One of the approaches exploits the proposed colorblind-friendly halftoning algorithm. The other one replaces DPwNCM in the proposed colorblind-friendly halftoning algorithm with DPw/oNCM. In other words, their difference is solely on whether the local noise characteristics is modulated with $R_{pd}(i,j)$. The quality is measured in terms of S-CIELab ΔE [21], Sparse Feature Fidelity (SFF) [22] and Feature Similarity Index ($FSIM_c$) [23]. S-CIELab ΔE is developed for evaluating the quality of a color halftone. When measuring the quality of a halftone in terms of SFF and $FSIM_c$, the halftone is first descreened with a matched HVS filter that fits for a specific setting of DPI and viewing distance parameters. The HVS filter is derived based on Campbell's contrast sensitivity function model of human eye [24].

Fig. 5 The difference between two color halftones produced by the same error diffusion-based halftoning algorithm but with different color separation schemes: (a) a CS scheme that minimizes $N_R+N_G+N_C+N_M$ (i.e the proposed colorblind-friendly CS scheme) and (b) a CS scheme that maximizes $N_R+N_G+N_C+N_M$ (a colorblind-unfriendly scheme). Each row shows (i) a halftone and how it looks to (ii) a protanope and (iii) a deuteranope. They are prepared for 600 DPI printing.

From Table 1, one can see that modulating noise characteristics results in a drop in visual quality, but the quality drop reduces as the viewing distance or the printing resolution increases. Obviously, at a fixed distance, there is a conflict between improving the visual quality of the halftone and enhancing the visibility of the hints embedded for colorblind people. On one hand, we do not want the hints to be visible to normal people. On the other hand, we want it to be visible to people of CVD. What we can achieve is to allow a viewer to adjust the viewing distance by himself/herself to resolve this conflict to some extent.

It is well accepted that color distortion is invisible when CIELab ΔE<3 [25]. The data in Table 1 show that, the color halftones produced with the two evaluated methods have no visible color distortion as compared with the original when they are printed at 600 DPI and viewed by normal people at a distance larger than 20 inches. However, the local noise patterns in our algorithm's output can be detected by colorblind people when they enlarge the printout or get close enough to it, which makes the proposed algorithm a colorblind-friendly halftoning algorithm.

VI. Conclusions

The conventional techniques used to develop colorblind aids do not take the printing process into account. We suggest making use of the halftoning step in the printing process to reduce the color distortion in the view of a colorblind person and embed hints in a printout for a colorblind person to distinguish the confusing colors. A halftoning algorithm is proposed in this paper to produce colorblind-friendly halftones for any kinds of images including natural images. Its output is colorblind-friendly in a way as follows:

- To people with normal vision, the color halftone looks the same as the original image when it is viewed at a reasonable distance.
- To people with CVD, the regional noise characteristics of the color halftone provides visible information to distinguish regions of different problematic colors when they get close to view the halftone or when they view it with a magnifier. A magnifier is common and it is much cheaper than a computer or a dedicated optical/electronic device that is required by current post-publication colorblind aids.

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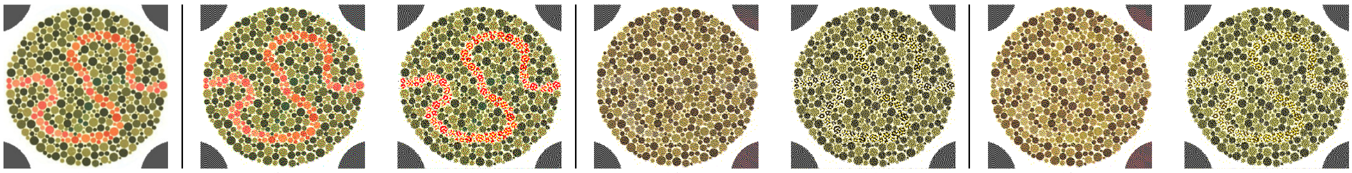
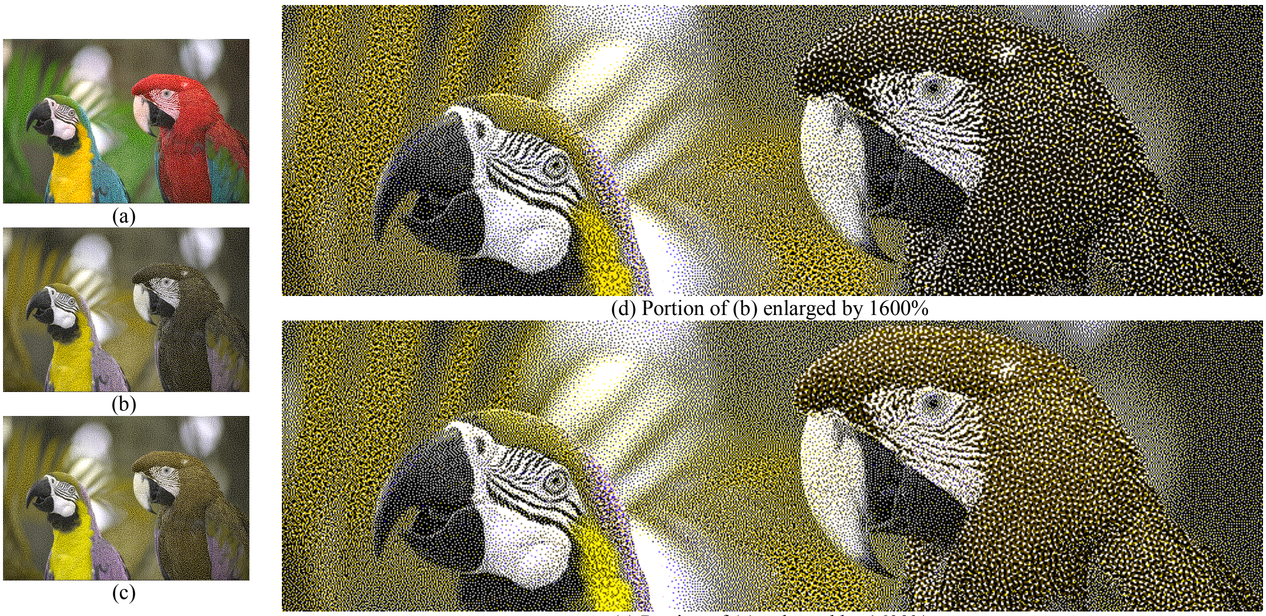


(a) (b) (c) (d) (e) (f) (g)

Fig. 6 Impact of different halftoning algorithms: (a) a colorblind test chart (the original); (b) the halftone produced with the native Matlab function; (c) the halftone produced with our colorblind-friendly algorithm. (d) and (e) are, respectively, how (b) and (c) look to a protanope. (f) and (g) are, respectively, how (b) and (c) look to a deuteranope.



(a) (b) (c)

(d) Portion of (b) enlarged by 1600%

(e) Portion of (c) enlarged by 1600%

Fig. 7 Output of the proposed color halftoning algorithm. Fig. 7(a) is the normal view at 600 DPI. Figs. 7(b) and 7(c) are, respectively, how Fig. 7(a) looks to a protanope and a deuteranope. Figs. 7(d) and 7(e) are, respectively, enlarged portions of Figs. 7(b) and 7(c) for better inspection.

DPI		72	96	150	300	600	1200	2400
S-CIELab ΔE	Ours with noise-characteristics modulation	31.0484	22.9247	12.5590	3.7028	1.0205	0.4321	0.5697
	Ours w/o noise-characteristics modulation	29.3208	21.0367	11.3001	3.3224	0.9596	0.4009	0.5220
SFF	Ours with noise-characteristics modulation	0.9911	0.9924	0.9949	0.9979	0.9991	0.9996	0.9997
	Ours w/o noise-characteristics modulation	0.9959	0.9971	0.9985	0.9994	0.9997	0.9998	0.9999
FSIMc	Ours with noise-characteristics modulation	0.9672	0.9731	0.9820	0.9918	0.9973	0.9993	0.9992
	Ours w/o noise-characteristics modulation	0.9730	0.9795	0.9886	0.9960	0.9989	0.9997	0.9997

Table 1. Quality of the color halftones obtained with the proposed halftoning algorithm and its variant when they are printed at different DPIs and viewed by normal people at a distance of 20 inches. The figures are the average of the results of the 24 Kodak full color images (available at http://r0k.us/graphics/kodak/). The figures are also valid for the cases when the halftones are printed at 300 DPI and viewed at distances 4.8, 6.4, 10, 20, 40, 80 and 160 inches respectively (from left to right).