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In Dependent Color Halftoning, Yellow Matters

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Abstract. *The most straightforward way of halftoning a color image is to halftone its cyan, magenta, and yellow channels independently. It has been shown in literature that halftoning the color channels dependently and using dot-off-dot strategy as much as possible will improve the print quality. Since a yellow dot on white substrate is much less visible than the other two colored dots in a number of methods only the C and M channels are halftoned dependently and the Y channel is halftoned independent of the two others. In this paper we will show that preventing the yellow dots from being printed on blue dots will improve the print quality and results in smoother textures. The color reproduction and the ink consumption for the proposed dependent color halftoning are also discussed.*

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INTRODUCTION

The most straightforward way of halftoning a color image is to halftone its color channels independently. In recent years there have been a number of papers proposing different halftoning methods that halftone the color channels in a dependent manner.[1–4] In Refs. 1 and 2 the authors showed that halftoning the *C* and *M* channels dependently results in smoother and more homogeneous textures. In Ref. 1 we already proposed a dependent color halftoning method and discussed the color reproduction when the *C* and *M* channels are halftoned dependently. In the proposed method in Ref. 1, however, the yellow channel was halftoned independently. In the present paper we are going to discuss the effect of the *Y* dots on the color reproduction and will show that preventing the *Y* dots from being placed on top of blue dots reduces the color noise and results in smoother textures compared to the case where the *Y* channel is halftoned independently. That means in the proposed dependent color halftoning, when the amount of cyan and magenta together is bigger than 1 (or 100%) the yellow dots are prevented from being placed on blue dots. In other cases, there are no blue dots and the yellow channel is halftoned independently as proposed in Refs. 1 and 2. In Ref. 1 we also showed that dependent color halftoning needs less ink to reproduce the same color compared to independent halftoning. The ink consumption for independent color halftoning and the proposed dependent color halftoning will also be discussed.

In the following, c, m, and y denote the coverage for cyan, magenta, and yellow when the channels are halftoned independently while c_d, m_d, and y_d denote these coverages when the channels are halftoned dependently.

All experiments have been carried out using HP Deskjet 5150. The CIEXYZ tristimulus values for the paper, primary colors, secondary colors, and black printed on office copy paper are shown in Table I. The *XYZ* values were measured using a spectrophotometer (Gretag Macbeth™ Spectrolino) with d65 light source. Hence, for correct color reproduction all images in this paper should be printed on the same type of paper and using the same type of printer. The images should also be viewed under d65 lighting conditions as in our measurements we used d65 light source. The images shown in this paper are printed at 150 dpi except for images in Figs. 1 and 2, which are printed at 100 and 72 dpi, respectively *(Figs 1 and 2 available in color as Supplemental Material on the IS&T website, www.imaging.org)*.

In this paper we assume that the color images are represented by their cyan, magenta, and yellow channels. Since we normally have our images in *RGB* format they are easily converted to *CMY* by

$$C = 1 - R,$$

$$M = 1 - G,$$

$$Y = 1 - B,$$

where R, G, and B are assumed to be scaled between 0 and 1. When the C, M, and Y channels have been halftoned to C_h, M_h, and Y_h it is possible to get the K_h channel by just putting a “1” in the positions of K_h where C_h, M_h, and Y_h all three are equal to 1. All figures in this paper are available in color on http://staffwww.itn.liu.se/~sasgo/JIST4196/.

DEPENDENT COLOR HALFTONING METHOD

In this section we just give a very brief description of the method. The method is thoroughly described in Ref. 1. The color halftoning method is an extension of the method for grayscale images. In the method for grayscale images the initial binary image is empty, that is there is no dot in the initial halftoned image. The problem of halftoning a grayscale image is described as placing a number of black dots on this empty initial image so that the final result “resembles” the original image. As the overall impression of lightness/darkness of the image it is very important the number of dots to be placed can actually be determined in

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Table I. CIEXYZ values for paper, cyan, magenta, yellow, blue, green, red, and black, when printed on office copy paper using DeskJet 5150. The *XYZ* values were measured using a spectrophotometer (Gretag Macbeth™ Spectrolino) with d65 light source.

	Paper	*C*	*M*	*Y*	*B*	*G*	*R*	*K*
X	81.19	27.02	32.79	65.92	15.21	19.02	31.04	2.82
Y	85.23	35.60	20.86	71.63	13.93	31.37	21.55	2.95
Z	96.64	75.29	31.86	21.80	37.20	19.58	14.22	3.13

advance. Now when we know the number of dots to be placed the question is where to place the 1's, i.e., the black dots. In this method the dots are placed iteratively in order to decrease the difference between the original image and the halftoned image. Therefore, the first dot is placed at the position of the darkest pixel in the original image. By the darkest pixel we mean the pixel that holds the largest value, i.e., the position of the maximum in the original image. Since the human eye acts as a low-pass filter the difference of the low-pass versions of the two images should be decreased. Therefore, the original image should be low-pass filtered prior to the method. Once the first dot is placed the filtered version of the current halftoned image is subtracted from the filtered version of the original image. This process will be referred to as the feedback process in the following. Then the position of the maximum in this modified image is found and the second dot is placed there and the feedback process is performed again. This will continue until the predetermined number of dots are placed and then the final halftoned image is achieved.

Due to the characteristics of this algorithm it is easily extended to a dependent color halftoning method. The strategy is to avoid dot-on-dot printing as much as possible and place the *C* and *M* dots homogeneously over the entire color image. Let c_d and m_d denote the coverage for the *C* and *M* color channels, respectively. When $c_d+m_d \leq 1$ dot-on-dot printing can completely be avoided. Like in the monochromatic case the numbers of dots to be placed in different tone regions of the *C* and *M* separations are calculated in advance. Then, the algorithm starts with finding the maximum pixel value in the *C* and *M* channels. Suppose that the maximum was found in the *C* channel. Now the feedback process is performed as before, but this time to both the *C* and *M* channels. By using appropriate filters the cyan and magenta dots can be placed homogeneously over the entire image and dot-on-dot can be avoided as much as possible.[1] When $c_d+m_d>1$ dot-on-dot cannot completely be avoided but we still avoid dot-on-dot as much as possible. In this case the amount of blue will be $b=c_d+m_d-1$ which means that the amount of pure cyan and pure magenta are $c'_d=c_d-b=1-m_d$ and $m'_d=m_d-b=1-c_d$, respectively. Thus the image with c'_d and m'_d coverage for cyan and magenta is halftoned dependently and the white dots in the resulting image are replaced by blue.[1] Since in the proposed method in the present paper we also want to prevent the yellow dots from being placed on blue dots, we first find the pixel positions where the result, i.e., the image after the *C* and *M* channels have been halftoned dependently, is blue, that is we find the positions where both cyan and magenta are present. Then we put a negative number at those positions in the *Y* channel and halftone the modified *Y* channel. Since in our method we seek for the maximum the negative numbers will not be found until all the other pixels are found, which means the yellow dots are prevented from being placed on blue dots as much as possible. In the following we discuss three different situations, namely; $(c_d+m_d \leq 1)$, $(c_d+m_d>1$ and $c_d+m_d+y_d \leq 2)$ and $c_d+m_d+y_d>2$.

$c_d+m_d \leq 1$

As was discussed earlier, in this case cyan dot on magenta dot (blue dot) can completely be avoided and thus the yellow channel can be halftoned independently. Something worth mentioning here is that since the yellow dots on white paper are much less visible than cyan and magenta dots the yellow channel should be halftoned differently. The reason why the yellow dots are much less visible is that the contrast between yellow dots and the paper is much less than the contrast between the two other colors and the paper. This can also be verified by comparing the CIE-*Y* values of these colors with that of the white paper shown in Table 1. The difference between the CIE-*Y* values of yellow and paper is much less than those between the two other colors and paper. In order to illustrate the difference we halftoned an image with $c=2\%$, $m=3\%$, and $y=4\%$. In the image shown in Fig. 1(a) the separations are halftoned independently. In the image shown in Fig. 1(b) all three channels are halftoned dependently, which means the yellow channel has also been treated like *C* and *M*. Although the color dots are more homogeneously placed in Fig. 1(b) this image does not look homogeneous at all. The reason is that, as explained, the yellow dots on white paper are much weaker than the other two. Therefore, the yellow channel should be halftoned differently. One way of doing that is to halftone the yellow channel independent of the two others, but prevent the yellow dots from being placed on top of the other two color dots as much as possible. Figure 1(c) shows this case. As can be seen this image is much more homogeneous than the ones shown in Figs. 1(a) and 1(b). By looking at the CIE-*Y* values in Table I we can see that the contrast between cyan and the white paper is almost the same as the contrast between green (cyan on yellow) and the white paper. The same is valid for magenta and red. Therefore, it is unnecessary to

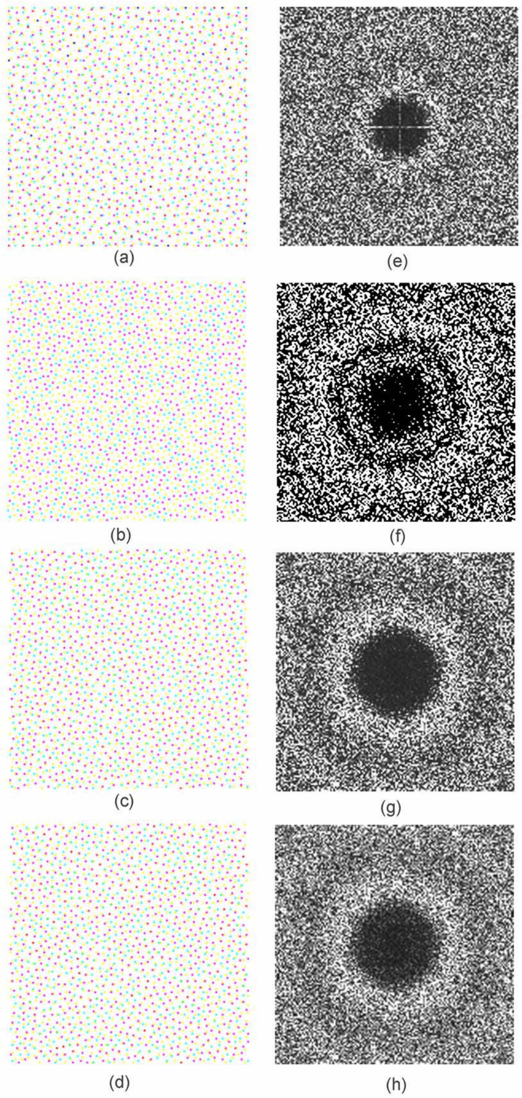


Figure 1. An image with $c=2\%$, $m=3\%$, and $y=4\%$ is halftoned. (a) All three channels are halftoned independently. (b) All three channels are halftoned dependently, which means the yellow channel has also been treated like C and M. (c) The C and M channels are halftoned dependently. The yellow dots are prevented from being placed on cyan and magenta. (d) The C and M channels are halftoned dependently and the yellow channel independent of the two others. (e), (f), (g), (h) The spectrum for the images shown in Figs. 1(a), 1(b), 1(c), and 1(d), respectively.

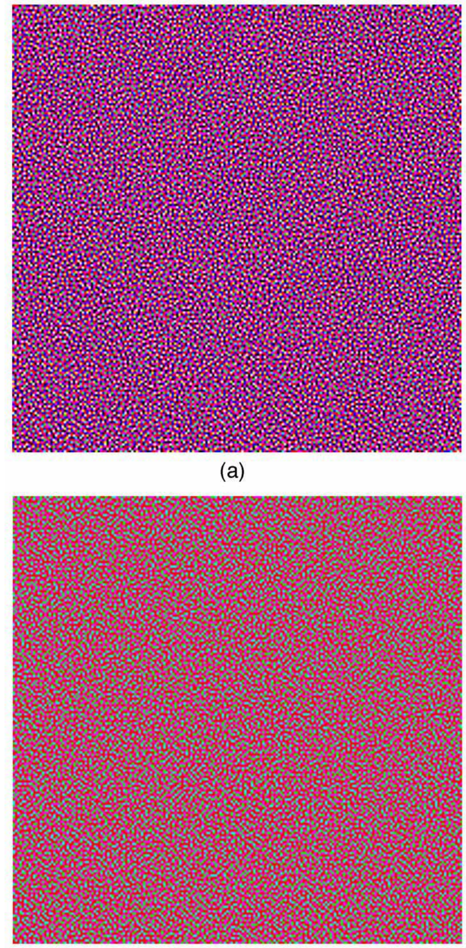
prevent the Y dots from being placed on cyan and magenta. This is also illustrated in Fig. 2 and discussed later in this section. Hence, the Y channel can be halftoned completely independent of the two other channels, see Fig. 1(d). Notice that in this image there are a number of green and red dots but they are hardly recognizable from cyan and magenta, respectively. In order to evaluate the structure of the halftone patterns we also show the spectrum of the images shown in Figs. 1(a)–1(d) next to the corresponding image. The spectrum was produced by first converting the color halftone patterns into black and white by replacing cyan and magenta dots with black. The yellow dots were ignored as they hardly have an impact. As can be seen in Figs. 1(e)–1(h) the half-

Figure 2. (a) 30% yellow is printed on a cyan background. (b) 30% yellow is printed on a magenta background. (c) 30% yellow is printed on a blue background.

tone pattern in Figs. 1(c) and 1(d) show a better blue noise characteristic.[5] For a good halftone pattern small low frequency noise as well as a circular symmetrical spectrum are required. As can be seen the spectra in Figs. 1(g) and 1(h) both have small noise in the low pass region (the darker the spectrum the smaller its magnitude) of their spectrum (the middle of the spectrum) and the shape of the spectrum is more circular symmetric compared to the others. The spectrum in Fig. 1(f), however, neither has a circular symmetrical shape nor is as noise free as the other spectra in the low frequency region. Although the spectrum in Fig. 1(e) has a relatively circular symmetrical shape the noise free low frequency region is smaller than that for Figs. 1(g) and 1(h). The noise in the low frequency region is also bigger than that of Figs. 1(g) and 1(h).

We already discussed that it would be unnecessary to avoid the yellow dots being placed on cyan or magenta. In order to illustrate that we printed 30% yellow on a cyan and magenta background, see Figs. 2(a) and 2(b), respectively. As can be seen the green and red dots are hardly visible. Table I reveals that the contrast between blue and black is much higher, see also Fig. 2(c), where 30% yellow have been placed on a blue background. That is why in our proposed method for this particular and similar printer we only prevent the yellow dots from being placed on the blue dots. If necessary, the yellow dots can be prevented from being placed on cyan, magenta, or both of them using the same strategy as being described in the following section. It has already been shown that if an image with $c_d=c$ and $m_d=m$ is halftoned independently and dependently the colors of the printed images will differ.[1] Let us now give an example. Assume that the C, M, and Y channels of an image with $c=0.4$, $m=0.8$, and $y=0.5$ are halftoned independently. Demichel's and Neugebauer's equations and the data shown in Table I give the resulting color $X=28.87$, $Y=24.97$, and $Z=28.41$.[6,7] Notice that in order for Neugebauer's equations to be applicable it is assumed that the coverage of each color in the equations is its effective coverage when printed. This means that the non-modified Neugebauer's equations used here assume dot gain to be negligible. This issue is taken up and alternative solutions are discussed in the final section.

Now if we ignore the effect of the Y dots on the resulting color and only consider C and M, then the same color (with a ΔE_{Lab} around 3) is achieved for $c_d=0.31$, $m_d=0.65$, and $y=0.5$. Notice that we use the index d for c and m but not for y because the C and M channels are being halftoned dependently, but not the Y channel. How to find c_d and m_d has already been shown in Ref. 1. Observe that in this case the C and M channels are halftoned dependently and then the yellow dots are placed independently. Therefore, by using Demichel's equations we can find out the coverage for each color. The coverage for cyan, magenta, yellow, red, green, and the white paper will be $0.31\times(1\text{-}0.5)=0.155$, $0.65\times(1\text{-}0.5)=0.325$, $(1\text{-}0.31\text{-}0.65)\times 0.5=0.02$, $0.65\times 0.5=0.325$, $0.31\times 0.5=0.155$, and $(1\text{-}0.31\text{-}0.65)\times(1\text{-}0.5)=0.02$. Blue and black never occur in this case. Thus the resulting color is $X=30.82$, $Y=27.30$, and $Z=32.04$. As can be noticed this color is a bit different from the color in the former case where the channels were halftoned independently. ΔE_{Lab} between these two colors is 3.4, which is not that high but still can be reduced. In order to do that, we involve yellow in our calculations as shown in the following equation. Here we just show the equation for X. The equations for Y and Z are exactly similar, only X's are replaced by Y and Z, respectively



(a)

(b)

Figure 3. (a) The C, M, and Y channels of an image with $c=0.4$, $m=0.8$, and $y=0.5$ are halftoned independently. (b) The C and M channels of an image with $c_d=0.31$, $m_d=0.69$, and $y=0.58$ are halftoned dependently and the Y channel independently. (Fig. 3 available in color as Supplemental Material on the IS&T website, www.imaging.org.)

$$X_{avg} = c_d(1-y)X_c + m_d(1-y)X_m + (1-c_d-m_d)yX_y + c_d yX_g + m_d yX_r + (1-c_d-m_d)(1-y)X_p, \qquad (1)$$

where X_{avg} is the X value for the average color. X_{c}, X_{m}, X_{y}, X_{g}, X_{r}, and X_{p} denote the X values for cyan, magenta, yellow, green, red, and paper, respectively. The aim is to find c_d, m_d, and y in order to match a target color X_{t}, Y_{t}, Z_{t}. In order to do that we find the best c_d, m_d, and y that minimizes the color difference between the target color and the average color. If $(L_{\mathrm{avg}}, a_{\mathrm{avg}}, b_{\mathrm{avg}})$ and $(L_{\mathrm{t}}, a_{\mathrm{t}}, b_{\mathrm{t}})$ denote the CIELab color coordinates for the average and the target colors, respectively, we find c_d, m_d, and y that minimize $\Delta E_{Lab}=\sqrt{(L_t-L_{avg})^2+(a_t-a_{avg})^2+(b_t-b_{avg})^2}$. Let us now go back to our example. If the target color is the color for the case where C, M, and Y channels are halftoned independently for an image with $c=0.4$, $m=0.8$, and $y=0.5$ then

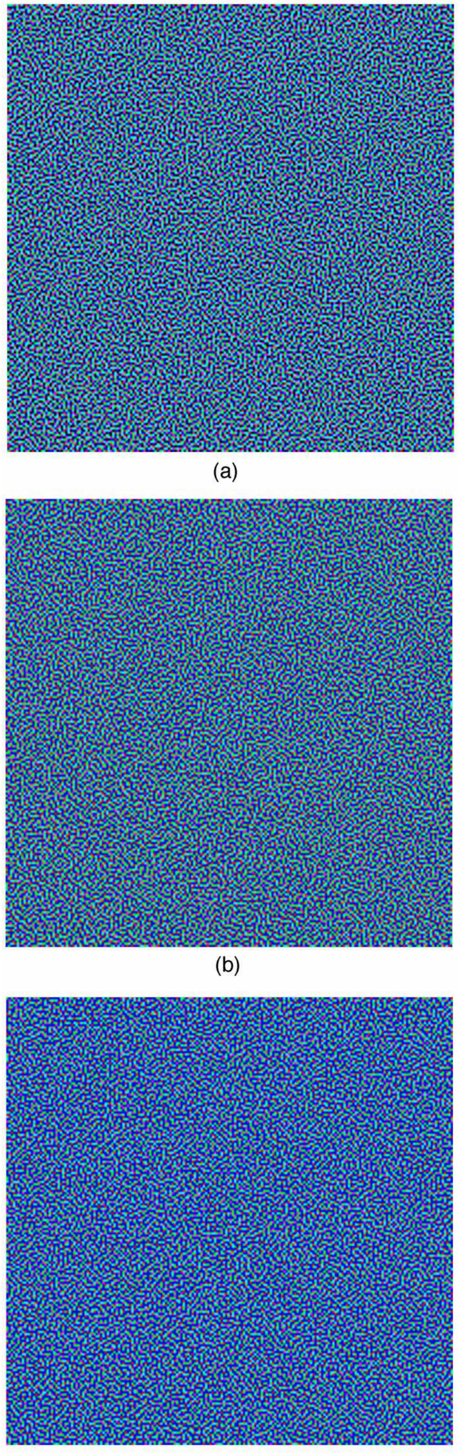


Figure 4. (a) The C and M channels of an image with $c_d=0.8$, $m_d=0.6$, and $y=0.4$ are halftoned dependently and the Y channel independent of the two others. (b) The C and M channels of an image with $c_d=0.8$, $m_d=0.6$, and $y_d=0.4$ are halftoned dependently, and the Y dots are prevented from being placed on top of blue dots. (c) The C and M channels of an image with $c_d=0.84$, $m_d=0.64$, and $y_d=0.32$ are halftoned dependently, and the Y dots are prevented from being placed on top of blue dots. (Fig. 4 available in color as Supplemental Material on the IS&T wesite, www.imaging.org.)

$c_d=0.31$, $m_d=0.69$, and $y=0.58$ gives the smallest ΔE_{Lab}, which is 0.22 for this example. As can be noticed the color difference is much smaller, although the previous one was also acceptable. Figure 3(a) shows an image with $c=0.4$, $m=0.8$, and $y=0.5$ being halftoned independently. In Fig. 3(b) the C and M channels of an image with $c_d=0.31$, $m_d=0.69$, and $y=0.58$ are halftoned dependently and the Y channel independently. As can be seen the image in Fig. 3(b) is almost the same color as the one in Fig. 3(a) but much more homogeneous. Observe that when we say they are the same color we mean their average colors are very close to each other. Looking at these images from a short distance may not reveal their average color. Therefore, in order to compare the colors the viewing distance should be long enough, or you probably need to peer to be able to see the average color. Note also that all measurements were carried out using d65 light source and therefore the correct colors are perceived under d65 lighting condition. Notice also that in our calculations it is assumed that nonmodified Neugebauer's equations are valid, which will be discussed more closely in the last section of the paper.

If in a similar example c and m are the same as before, i.e., $c=0.4$, $m=0.8$, but $y=0.8$, then not taking into account yellow in the calculations will result in $c_d=0.31$, $m_d=0.69$, and $y=0.8$. ΔE_{Lab} in this case is 4.9, which is a little bit too high and the human observer can see the difference.[8] This difference can be reduced to 0.18 if we allow c_d+m_d to be greater than 1. This example is taken up at the end of the next section again.

$c_d+m_d>1$ and $c_d+m_d+y_d\leq 2$

In this case the coverage of blue (cyan on magenta) is c_d+m_d-1. The coverage of pure cyan and pure magenta is therefore $c'_d=c_d-(c_d+m_d-1)=1-m_d$ and $m'_d=m_d-(c_d+m_d-1)=1-c_d$, respectively. As being discussed in Ref. 1 the C and M channels of an image with $c'_d=1-m_d$ and $m'_d=1-c_d$ are halftoned dependently and the white pixels in the resulting image are then replaced by blue. Let us show two images before we discuss this case in detail. In Fig. 4(a) the C and M channels of an image with $c_d=0.8$, $m_d=0.6$, and $y=0.4$ are halftoned dependently and the Y channel independent of the two others. In Fig. 4(b), as in the former case the C and M channels of the same image are halftoned dependently, and the Y channel is also halftoned "dependently" in a way that the yellow dots are prevented from being placed on blue dots. How our proposed method in Ref. 1 can be modified to do that is already discussed in previous sections. As can be seen the image in Fig. 4(b) is much smoother than the one in Fig. 4(a). Since no color correction has been made these two images have different colors. Assume that we want to find the best c_d, m_d, and y_d, with $c_d+m_d>1$ and $c_d+m_d+y_d\leq 2$ that matches a target color X_t, Y_t, and Z_t. Since $c_d+m_d>1$ then after halftoning C and M dependently there will not be any white dots. When the Y dots are then placed, there will not be any white dots, yellow dots, or black dots. There will not be any black dots because in our proposed method the Y dots are avoided from being placed on blue dots. Also notice that since $c_d+m_d+y_d\leq 2$ black dots can completely be avoided. Since the yellow dots are not placed on blue dots, they are placed on either magenta or cyan, and thus in the Demichel's equations instead of y_d, we should use $y_n = y_d/[(1-c_d)+(1-m_d)] = y_d/(2-c_d-m_d)$, assuming that $(c_d+m_d) \neq 2$.

The coverage of pure cyan and pure magenta after the Y dots are placed is therefore $(1-m_d)(1-y_n)$ and $(1-c_d) \times (1-y_n)$, respectively. The coverage for green and red is $(1-m_d)y_n$ and $(1-c_d)y_n$, respectively. The coverage for blue is as before c_d+m_d-1. The case $(c_d+m_d)=2$ is possible if and only if $c_d=1$, $m_d=1$, and $y_d=0$. y_d must be zero since $c_d+m_d+y_d \leqslant 2$ and therefore $X_{avg}=X_b$.

Hence, the following equations are obtained. Here we just show one of the three equations; the other two are obtained by replacing X, with Y and Z

$$\begin{aligned} X_{avg} = {} & (1-m_d)(1-y_n)X_c + (1-c_d)(1-y_n)X_m \\ & + (1-m_d)y_nX_g + (1-c_d)y_nX_r + (c_d+m_d-1)X_b \\ & \text{if } (c_d+m_d) \neq 2. \end{aligned} \tag{2}$$

Otherwise, if $(c_d+m_d)=2$, then $X_{avg}=X_b$, where X_{b} denotes the X value for blue, the other parameters are as before and $y_n = y_d/(2-c_d-m_d)$. c_d, m_d, and y_d are now found so that ΔE_{Lab} between the average color and the target color is as small as possible.

Let us go back to our example with $c_d=0.8$, $m_d=0.6$, and $y=0.4$. In the image shown in Fig. 4(a), only C and M are halftoned dependently, therefore before the Y dots are placed the coverage for cyan, magenta, and blue is 0.4, 0.2, and 0.4, respectively. Then Y dots (coverage 0.4) are placed independently, therefore the coverage for cyan, magenta, blue, green, red, and black is $0.4 \times (1\text{-}0.4) = 0.24$, $0.2 \times (1\text{-}0.4) = 0.12$, $0.4 \times (1\text{-}0.4) = 0.24$, $0.4 \times 0.4 = 0.16$, $0.2 \times 0.4 = 0.08$, and $0.4 \times 0.4 = 0.16$, respectively. If we assume this to be our target color then we have $X_{\mathrm{t}}=20.05$, $Y_{\mathrm{t}}=21.6$, and $Z_{\mathrm{t}}=35.59$. Equation (2) and its corresponding equations for Y and Z give $c_d=0.84$, $m_d=0.64$, and $y_d=0.32$ with $\Delta E_{\mathrm{Lab}}=0.52$. Figure 4(c) shows this image being halftoned dependently where the yellow dots are prevented from being placed on top of blue dots. As can be seen this image is the same color as the one in Fig. 4(a) and is much more homogeneous.

Recall the example at the end of the previous section with $c=0.4$, $m=0.8$, and $y=0.8$. We discussed that the best choice there, if yellow was not involved in the calculations, would give $\Delta E_{\mathrm{Lab}}=4.9$. If we now allow $c_d+m_d>1$ and use Eq. (2), we find that $c_d=0.34$, $m_d=0.74$, and $y_d=0.88$ would give $\Delta E_{\mathrm{Lab}}=0.18$.

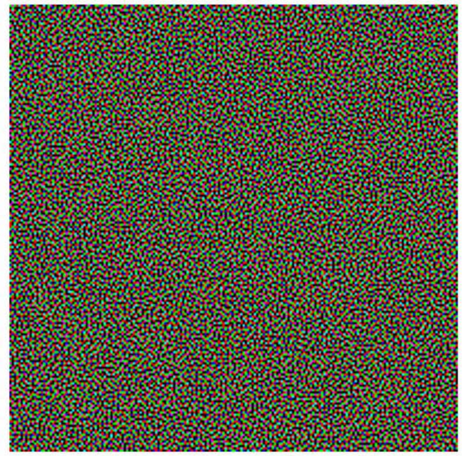
$c_d+m_d+y_d>2$

In this case black dots cannot be completely avoided, but they are still avoided as much as possible and therefore the coverage of black will be $c_d+m_d+y_d-2$. The coverage of blue before the Y dots are placed is c_d+m_d-1. Parts of it will be black after the Y dots are placed and remained will be $b=c_d+m_d-1-(c_d+m_d+y_d-2)=1-y_d$. The amounts of cyan and magenta dots before the Y dots are placed are $1-m_d$ and $1-c_d$, respectively. The remainder of the yellow dots $y_d-(c_d+m_d+y_d-2)=2-c_d-m_d$, which is exactly equal to the amount of cyan and magenta together, is then placed on either cyan or magenta. It means that there will not be any cyan, magenta, or yellow dots, instead all cyan dots become green (yellow on cyan) and all magenta dots become red (yellow on magenta). Thus, the following equations are obtained. Here we just show one of the three equations; the other two are obtained by replacing X's, with Y and Z

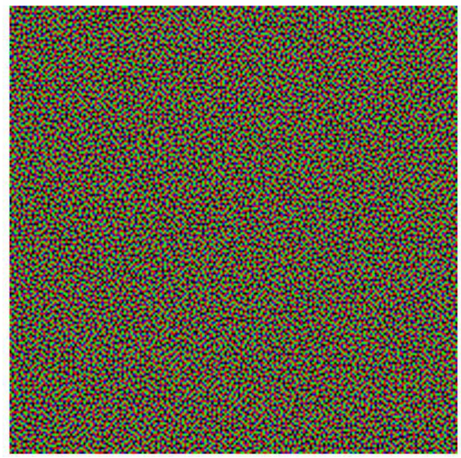
$$\begin{aligned} X_{avg} = {} & (1-m_d)X_g + (1-c_d)X_r + (1-y_d)X_b \\ & + (c_d+m_d+y_d-2)X_k, \end{aligned} \tag{3}$$

where X_k denotes the X value for black.

Let us now give an example. In Fig. 5(a) the C and M channels of an image with $c_d=0.7$, $m_d=0.7$, and $y=0.8$ are halftoned dependently and the Y channel independently. That means the coverage for pure cyan, pure magenta, and blue after halftoning C and M channels dependently are 0.3, 0.3, and 0.4, respectively. Demichel's equations give us the target color and Eq. (3) and its corresponding equations for



(a)



(b)

Figure 5. (a) The C and M channels of an image with $c_d=0.7$, $m_d=0.7$, and $y=0.8$ are halftoned dependently and the Y channel independently. (b) The C and M channels of an image with $c_d=0.66$, $m_d=0.68$, and $y_d=0.81$ are halftoned dependently, and the Y dots are prevented from being placed on top of blue dots as much as possible. (Fig. 5 available in color as Supplemental Material on the IS&T website www.imaging.org.)

(a)

(b)

Figure 6. A real image has been halftoned. In (a), only C and M channels are halftoned dependently. In (b), the C and M channels are halftoned dependently, and the Y dots are prevented from being placed on top of blue dots as much as possible. (Fig. 6 available in color as Supplemental Material on the IS&T website www.imaging.org.)

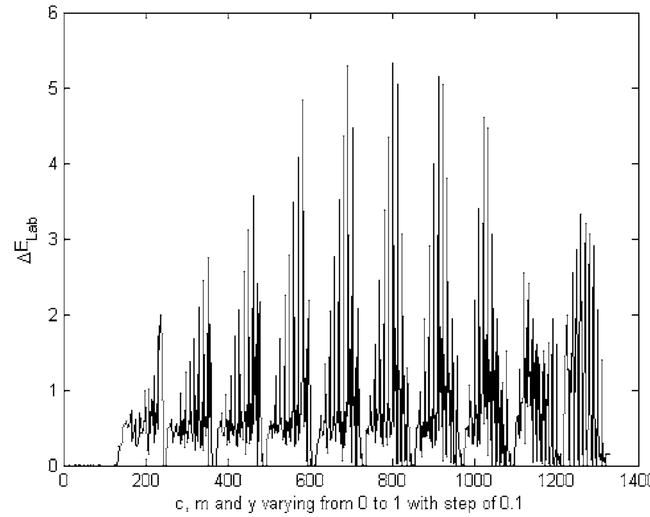


Figure 7. ΔE_{Lab} when c, m, and y vary from 0 to 1 with a step of 0.1 is shown. For each c, m, and y the color when using independent color halftoning is found. This color is then used as the target color and the best ΔE_{Lab} to match this target color using dependent color halftoning is calculated. (Fig. 7 available in color as Supplemental Material on the IS&T website www.imaging.org.)

Y and Z give $c_d=0.66$, $m_d=0.68$, and $y_d=0.81$. Figure 5(b) shows an image with these c_d, m_d, and y_d being halftoned, where the C and M channels are halftoned dependently and the Y dots are prevented from being placed on top of blue dots as much as possible. In this example we have $0.66+0.68+0.81-2=0.15$ (15%) black. As can be seen the image in Fig. 5(b) is more homogeneous than that in Fig. 5(a) although the difference is not as obvious as in the previous examples, because the black dots could not completely be avoided.

Images in Fig. 6 show a real image being halftoned. In Fig. 6(a), only C and M channels are halftoned dependently while in the image shown in Fig. 6(b) all three channels are halftoned dependently, as described before. Obviously the latter image is much more homogeneous than the former one, which can be seen in many parts of the image, for example the tablemats.

Color Difference

We start this section by asking whether it is possible to reproduce all colors that are reproduced when C, M, and Y channels are halftoned independently with the proposed dependent color halftoning. In order to answer this question we varied c, m, and y from 0 to 1 with a step of 0.1. For each c, m, and y we calculated the resulting color assuming that the three channels are halftoned independently. This color is then used as the target color and the best c_d, m_d, and y_d and the smallest ΔE_{Lab} to match this target color are found. The smallest ΔE_{Lab} for these cases are shown in Fig. 7. As being noticed ΔE_{Lab} is smaller than 2 in many cases and the average ΔE_{Lab} is 0.6. Observe that the just noticeable difference for ΔE is said to be around 2.3.[8] However, the largest ΔE_{Lab} is around 5. By investigating the results more closely we found that ΔE_{Lab} is bigger than around 2 or 3 only when y is very close to 1. The largest ΔE_{Lab} actually occurs when $c=0.7$, $m=0.6$, and $y=1$. In this case the best c_d, m_d, and y_d are 0.62, 0.6, and 1, respectively. In order to find the best c_d, m_d, and y_d we varied them with a step of 0.01. Smaller steps could probably give a slightly smaller ΔE_{Lab} but would slow down the computations considerably. For the case with largest ΔE_{Lab}, in the dependent case before the Y dots are placed, we only have cyan, magenta, and blue. Therefore, when the Y dots (coverage 100%) are placed we will only have green, red, and black. In the independent case we have all eight colors and therefore it is possible that the color matching will cause a big ΔE_{Lab}. This of course depends on the measured data and therefore for other printers it might not be the case. We can conclude that there are few colors that can be reproduced by independent halftoning but not with dependent halftoning and the average ΔE_{Lab} is very small. There are, on the other hand, colors that can be reproduced by dependent and not by independent halftoning. In our proposed halftoning method it is possible to use independent halftoning in some parts of an image and dependent halftoning in the rest of it.[1] Therefore, if there is a target color in a part of an image that cannot be reproduced by dependent halftoning, the method can simply halftone that part independently, and vice versa.

In order to show how these two different approaches reproduce colors we have done two simulations. In the first one we varied $c=c_d$ and $m=m_d$ from 0 to 1 with a step of 0.1 and kept $y=y_d$ equal to 0. Figures 8(a) and 8(b) show the a and b values for reproduced colors in an ab-diagram (a

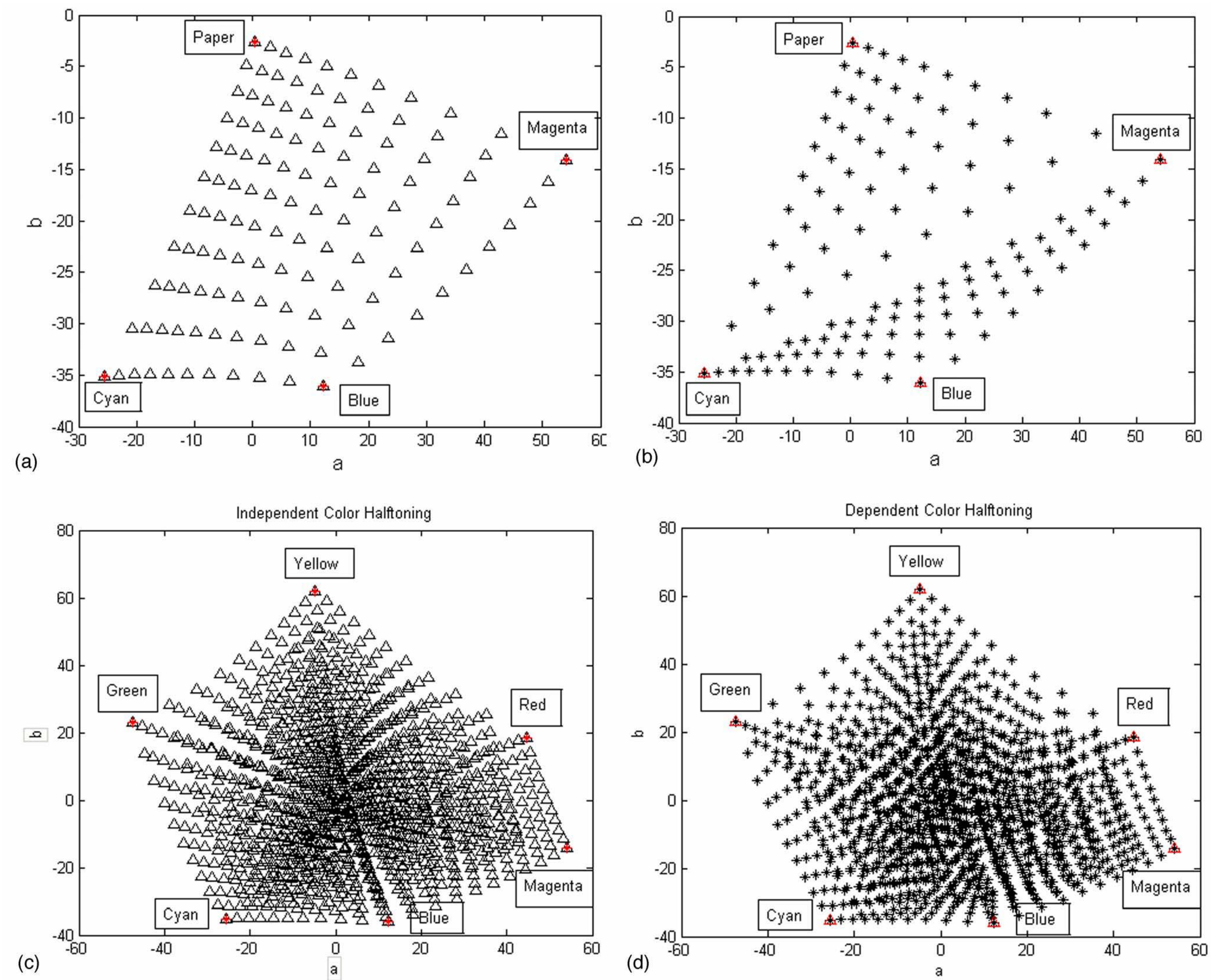


Figure 8. $c=c_d$ and $m=m_d$ vary from 0 to 1 with a step of 0.1 while $y=y_d$ is equal to 0. The (a) and (b) color coordinates for the reproduced colors using independent and dependent color halftoning are plotted in (a) and (b), respectively. $c=c_d$, $m=m_d$, and $y=y_d$ vary from 0 to 1 with a step of 0.1. The (a) and (b) color coordinates for the reproduced colors using independent and dependent color halftoning are plotted in (c) and (d), respectively. (Fig. 8 available in color as Supplemental Material on the IS&T website www.imaging.org.)

and b are the a and b color coordinates in CIELab) for independent and dependent halftoning, respectively. Figures 8(c) and 8(d) show the same diagrams while $y=y_d$ is also varying from 0 to 1 with a step of 0.1. As can be seen, especially in Figs. 8(a) and 8(b), these methods fill the color gamut differently. Of course, if a smaller step for varying $c=c_d$, $m=m_d$, and $y=y_d$ were used there would have been more colors filling the empty spaces in the color gamut. Here, we chose to have a bigger step just to be able to illustrate the difference between these two ways of halftoning in filling the color gamut.

Ink Consumption

In Ref. 1 we showed that when C and M channels are halftoned dependently less ink is needed to reproduce the same color as independent halftoning. In that case yellow was ignored. In order to investigate ink consumption for the proposed dependent color halftoning we simulated the ink consumption by varying c, m, and y from 0 to 1 with a step of 0.1. Then for each c, m, and y, we calculated the best c_d, m_d, and y_d. Figure 9(a) shows the difference $(c+m+y)-(c_d+m_d+y_d)$. The difference is mostly positive and the average is 0.047, which means about 5%. That means independent color halftoning consumes more ink, if only cyan, magenta, and yellow inks are used. But almost all printers use a fourth color, i.e., black, instead of cyan, magenta, and yellow on top of each other. In this case the real ink consumption for the independent case is

$$(c+m+y)-2(c\,.\,m\,.\,y), \qquad (4)$$

where $c.m.y$ (the product of c, m, and y) is the amount of black that replaces cyan, magenta, and yellow dots when all three are present. Since black is replacing C, M, and Y dots the sum of c, m, and y should be reduced by twice the amount of black. In the dependent case the real ink

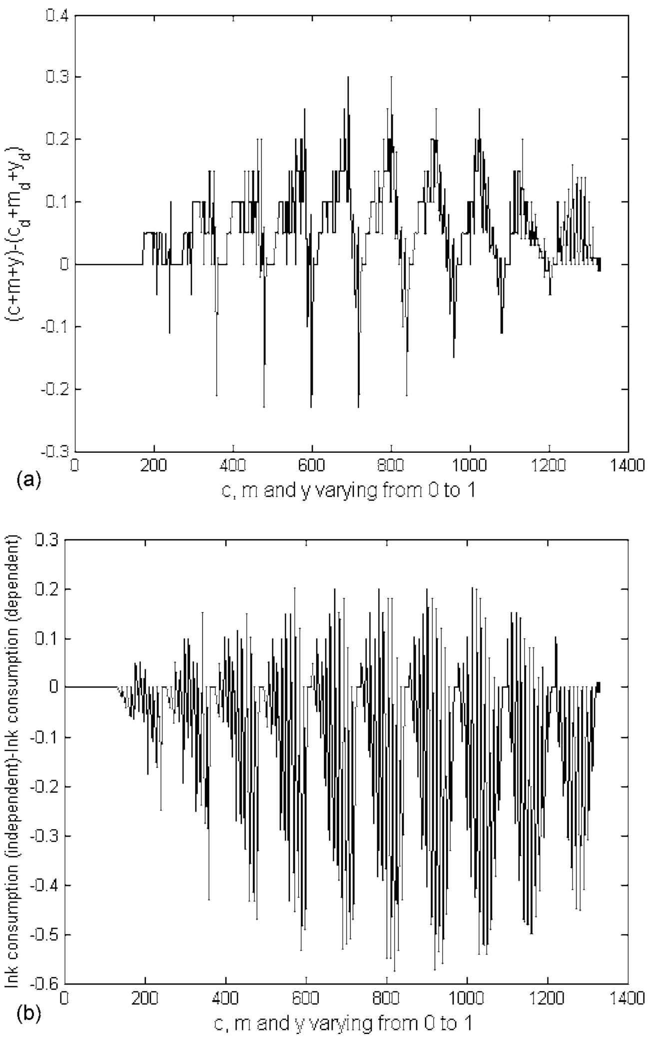


Figure 9. (a) The difference between the color consumptions for independent and dependent color halftoning assuming there is no black ink. (b) The difference between the color consumptions for independent and dependent color halftoning when black ink replaces cyan, magenta, and yellow in positions where all three are present. (Fig. 9 available in color as Supplemental Material on the IS&T website www.imaging.org.)

consumption is

$$(c_d + m_d + y_d) - 2(c_d + m_d + y_d > 2)(c_d + m_d + y_d - 2), \tag{5}$$

where

$$(c_d + m_d + y_d > 2) = \begin{cases} 1 & \text{if } (c_d + m_d + y_d > 2) \\ 0 & \text{otherwise} \end{cases}.$$

This means when $(c_d+m_d+y_d \leq 2)$ the second term in Eq. (5) is zero, because there is no black dot, and the ink consumption is simply the sum of the amount of cyan, magenta, and yellow. When $(c_d+m_d+y_d>2)$, twice the amount of black, which is $(c_d+m_d+y_d-2)$, is reduced from the sum. Figure 9(b) shows the difference between the real ink consumption for independent and dependent color halftoning. As can be seen here, the difference is mostly negative, which means independent halftoning needs less ink. The average difference in ink consumption is -0.098, i.e., about -10%.

SUMMARY AND DISCUSSION

It has previously been discussed that halftoning the *C* and *M* channels of an image dependently can produce smoother and more homogeneous textures.[1,2,9] In this paper we have shown that if the yellow dots are prevented from being placed on top of blue dots smoother and more homogeneous textures are obtained even for textures with $c_d+m_d > 1$. The color reproduction of the dependent color halftoning has been discussed and compared with that of the independent color halftoning. In the calculations Demichel's and nonmodified Neugebauer's equations have been used. Demichel's equations work perfectly when the color dots are placed independent of each other, which we also have checked for all images in Figs. 3–5. The non-modified Neugebauer's equations assume that there is no dot gain involved in the process. At the resolution we used, i.e., 150 dpi, dot gain does not affect our calculations considerably, as the color matching seems to work fairly well. If the dot gain cannot be neglected, then the best c_d, m_d, and y_d to match a certain target color are actually the real coverages after print, including both physical and optical dot gain. The commanded c_d, m_d, and y_d should therefore be found using the corresponding dot gain curve.[10] Another way of taking into account the effect of dot gain would be to use the modified Neugebauer's equations (based on the Yule-Nielsen model).[11] If so, an appropriate correction factor n should be found and then put into Eqs. (1)–(3) in the present paper. For instance, putting the correction factor n into Eq. (1) gives the following equation:

$$X_{\text{avg}} = [c_d(1-y)X_c^{1/n} + m_d(1-y)X_m^{1/n} + (1-c_d-m_d)yX_y^{1/n} + c_d y X_g^{1/n} + m_d y X_r^{1/n} + (1-c_d-m_d)(1-y)X_p^{1/n}]^n. \tag{6}$$

Notice that, Eq. (6) would be valid if the correction factor was found to make the model represent both physical and optical dot gain, which is not actually the case since the model only aims to represent the Yule-Nielsen effect (or optical dot gain). If so, c_d, m_d, and y found from Eq. (6) would only give us the physical dot coverage for each color after print, that means including physical dot gain. However, sometimes a correction factor n is used to make the model represent both physical and optical dot gain. If it is possible to find such a correction factor, then Eq. (6) could be used to find the commanded coverages.

It has also been shown in the present paper that the real ink consumption is less for independent halftoning, when black ink is printed instead of cyan, magenta, and yellow on top of each other. The method proposed in Ref. 1 is very flexible and preventing the *Y* dots from being placed on blue dots is done by slight modification of the method, which does not have any impact on the speed of the halftoning process.

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