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Color Enhancement of Digital Images by Experts and Preference Judgments by Observers

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Abstract. *We studied the preference judgment of pictorial images by image experts and naive observers. We first asked image experts to improve pictorial images the way they preferred. Then, we showed the different versions of each image to naive observers and asked them which version they preferred. To enhance an image, an expert divides it into large areas of interest, which mainly correspond to natural colors. To assess their preference judgments, naive observers principally focus on natural colors like sky, skin, or grass when present. A closer analysis of the digital image files showed that the segmentation process used by the experts allows to apply different corrections on the different objects. We used the previous work on memory colors by Yendrikhovskij and we showed that, to enhance an image, an expert moves the color space coordinates of identified zones towards those of memory colors corresponding to the objects being represented. The expert also follows some rules: the corrections must be plausible inside each segment and for the whole image, in relation with the illuminant of the scene. The images are accepted by observers in relation with the presence of memory colors and when the treatment of the whole image seems coherent.* **© *2006 Society for Imaging Science and Technology.***
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INTRODUCTION

Image quality may be influenced by technical factors like the resolution of a printer or the number of colors of a display, as well as individual factors like age, culture or personal preference. In order to be able to optimize image treatments before printing, we need to investigate and to quantify the importance of individual factors. We concentrate on the procedure that can improve color image quality and increase preference from an observer's point of view.

Quality corrections of images often concern experiments with images displayed on screen.[1–4] Some works, dealing with digital images printed on paper, were reported in the literature.[5–8] In general, the attributes that are supposed to influence quality and preference are tested with observers, but the variations of those attributes are often systematically incremented and are applied on the whole image.[2,5–7] However, professionals working in the image publishing industry, who are responsible for the quality to be approved by the public, do not improve images this way. Image experts first start by dividing the images into large zones and they manipulate each zone separately in order to enhance the final quality of the image. Throughout this paper, we name "image experts" the graphic experts responsible for colour enhancements that improve the image. The aim of this paper is to better understand the factors underlying the expert's behavior in image enhancement, and the preference of images by naive observers.

We first describe an experiment with image experts. The aim is to analyze their practice in image's enhancement. We asked image experts to improve eight pictorial images the way they preferred, and to save each intermediate version of enhancement. Then, we showed images produced by one expert to naive observers and asked them: Which image do you prefer among the different versions? The observers gave us their preference judgement on the images produced by the expert. We obtained an image database associated with preference judgements. To further analyze the expert's work,

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Plate 1. Test images used in the experiments.

we studied color and lightness changes of corrected images, associated with the theory of memory colors. Those studies lead to understand the factors underlying image preference and the enhancement of image quality for printed images.

This paper is divided into four sections before the conclusion. The first one presents the experiment of image enhancement made with experts, the second one presents the experiment of visual scaling made by naïve observers. The third one presents the tools used for the quantitative analysis of expert's corrections and the fourth one is the discussion on expert's image enhancement related to image preference.

EXPERIMENT 1: IMAGE ENHANCEMENT BY EXPERTS

Material for Image Processing and Printing Used Throughout the Experiment

The printer used for this experiment was the Epson Stylus Pro 7600 ink jet printer. It was driven by the "Postershop" Raster Image Processing (RIP) software from Océ. We used Semi gloss Premium Epson Photo Paper 162 g and pigmented inks Ultrachrome that are stable to light. The printer was calibrated and characterized with the RIP's calibration menu and the spectrophotometer Gretag Spectroscan.

We used eight pictorial images of various indoor and outdoor scenes; they are shown in Plate 1. The files were chosen from Photodisc image CD n°15 and 60, and from Kodak Photo CD Photo Sampler V2. They were RGB images in JPG or PCD format at 1536×2296 pixels or 2048×3072 pixels. Upon manipulations in Photoshop software, all images were transformed in CMYK Tiff files because the experts are used to work using a CMYK workflow. To separate the images from RGB to CMYK, we used the color management module of Adobe Photoshop and two ICC profiles. We transformed images from the RGB source profile Adobe RGB 1998 to the CMYK destination profile Epson Premium Semi gloss photo paper. We used the Adobe color management engine in the perceptual mode. We obtained CMYK images that could be printed on the 7600 printer without further color space manipulations. The advantage of a CMYK workflow is to avoid gamut mapping problems while printing. The final characteristics of images were 17×26 cm, with a resolution of 220 dots per inch.

Image Enhancement by Experts

We gave the eight digital image files to two image experts. The first expert works in a pre-press company that treats images for travel, television, and art magazines. She is graduated from a fine art school. She has been working for 14 years in publishing industry. The second expert works in a major advertising company and is graduated from a photographic school. She has been working for 5 years. Their work consist in enhancing digital image files before printing.

The experts performed the experiment in their own company, using Adobe Photoshop 6 software to transform the CMYK images. The experts used a color calibrated workstation. The screen and Photoshop software were tuned in order to simulate the printed result on the Epson 7600 seen under D50 daylight. Although screen proofing has limitations and cannot be considered as perfect, this is the way those experts are used to work in their companies. Furthermore, we validated the equivalence between the images seen on screen and the printed images, with the help of the experts. We asked the experts to judge the printed images that they corrected on screen, using the same psychophysical experiment than for naïve observers (described in the next chapter, Experiment 2). The experts were coherent with their own corrections while judging printed images, so we concluded that screen proofing did not introduce unwanted bias for the context of our research.

We asked the experts to improve the images the way they wanted in order to produce the image they prefer. The experts had to save each intermediate version of enhancement, each time they thought it was an important step of quality improvement. We registered the steps of enhancement in order to evaluate the influence of each image manipulation on observers' preference. The experts were also asked to produce alternative versions of the same image. They were free to produce another interpretation of the image enhancement or to do some trials about the influence of some color changes. Those alternative versions allow to add data to understand image preference of observers. Each expert provided between five and eight versions of the same image. They commented their manipulations while they were working.

Results: Experts Strategy While Correcting Images

Before modifying an image, the experts first think about the purpose of the image. The first expert may treat images differently when dedicated to travel magazines or when dedicated to advertising. She explained for example that she usually increases saturation for travel images, even if this leads

to something unnatural. Her methodology confirms that image manipulations should be linked to the purpose of images.[2] In this experiment, we did not give any particular context to the experts. We only told them that those images would be evaluated by naïve observers. The experts first treated images the way they would prefer and the alternative versions usually correspond to alternate interpretations of images. The different steps of corrections made by the first expert are summarized in Table I.

The two experts started the image corrections by segmenting them in a few large zones of interest. They usually divided them into only two or three parts. The segmentation was made by drawing masks in Photoshop, and those masks allowed the experts to work only on the image parts they chose. Both experts segmented the images in a similar way, as shown in Fig. 1. When we look at the parts isolated by the experts, we see that they mainly correspond to natural elements like the sky, the grass and the skin when they were present. In all the images where the sky was present, it became a segmented part. In three out of the four images with grass or foliage, these elements became a segmented part. The experts focused particularly on those natural colors, they spent a lot of time correcting skin tones, for example.

Furthermore, the experts almost ignored some other parts, like the clothes in the Girl image, or the Taj Mahal color. However, the Taj Mahal building seems to be the principal subject of the image but the two experts did not correct it. The whole Taj Mahal image had a slight red color cast that leads to an ambiguity in the interpretation of the image. This could be an image taken in red sunset with a Taj Mahal constructed with white stone, or it could be an image taken in the afternoon with Taj Mahal built with pink stone. The experts did not know what the color of the real Taj Mahal was, so they did not correct it. We did not add the full color images produced by the experts as it is very difficult to show the colors produced by our printing system with respect to the printing process of the journal.

The experts usually correct the images using Photoshop's menus called "tonal curves," "brightness/contrast," and "hue/saturation." Experts are working on CMYK image data, related to the printer color space (the working space in the Color setting menu in Photoshop is the ICC printer profile). The Photoshop menus present an interface that allows to scale attributes called contrast or saturation and that adjusts automatically the CMYK values of the image. The exact transfer functions are designed by Adobe and are unknown. We analyzed the modifications made by those tools in the $L^*a^*b^*$ color space with Matlab routines in the following chapter "Quantitative analysis of expert's corrections." The experts corrected the images by changing attributes like hue, lightness, contrast or saturation. They changed attributes of segmented parts until they thought the whole image would be the one they preferred. It was an iterative process and the experts integrated the influence of adjacent color zones in corrections. For example, see Table I, in the Baby image, the expert first changed background color of the blanket to take into account its influence on the skin color of

Table I. Images transformations by first expert, with segmented parts and the preference rank of naive observers. The steps of the main image corrections are called A1, A2, etc. The steps of alternative corrections are called B1, B2, etc. Other alternative corrections are called C1, C2, etc. The original image is noted 0.

	Image	Segmented part	Transformations	Rank
Hand	0	—	—	4
	A1	1	Change background color	2
	A2	2	Change skin color	1
	B1	2	Increase hand contrast from A2	3
	C1	all	Change global color from 0	5
	D1	all	Change global color from 0	1
Garden	A1	1.3	Change grass color	5
	A2	3	Change hose pipe color	4
	A3	1	Change red wall color	3
	A4	all	Increase global contrast	2
	A5	2	Change grass color	1
	B1	all	Change global contrast from 0	6
Baby	0	—	—	3
	A1	1	Remove color from blanket	5
	A2	2	Change skin color	2
	A3	3	Change hair color	1
	B1	1	Modify blanket color from A3	6
	C1	2	Change skin color from A3	4
Girl	0	—	—	3
	A1	2	Change skin color of face	1
	A2	2	Change color of teeth	2
	A3	1	Change background saturation	4
	B1	all	Change color from A3	6
	C1	all	Change global color from 0	5
Lighthouse	A1	all	Change white point of image	4
	A2	1	Change sky color	2
	A3	all	Change global contrast	1
	A4	2	Change lighthouse color	3
	B1	all	Change global contrast from 0	6
	C1	3	Change grass color from A4	5
Buddha	A1	2	Remove color from stone	2
	A2	1	Change sky color	1
	A3	all	Change global contrast	4
	B1	1	Change sky color from 0	6
	B2	3	Change clothe color	5
	B3	2	Change shadow color	3
Statue	0	—	—	1
	A1	1	Change sky color	2
	A2	2	Change background contrast	3
	A3	2	Change background saturation	4
	A4	2	Change green color tree	5
	B1	all	Change global color from 0	6
Taj Mahal	0		—	2
	A1	all	Change global contrast	3
	A2	1	Change sky color	6
	A3	2	Change grass and water color	4
	B1	all	Change color contrast from 0	5
	C1	2	Change grass and sky from 0	1

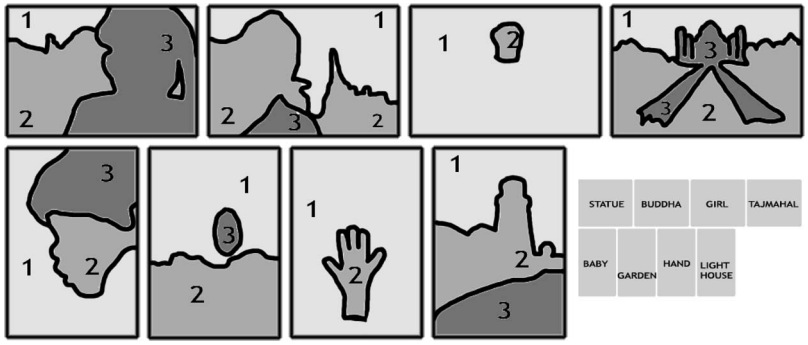

Figure 1. Segmentations made by the first expert. The second expert made similar segmentations. The numbers in segmented parts are used in Table I.

the baby. The expert modified the grass color in image Garden in the first step of correction and again in the last step of correction, in order to integrate the influence of the context on the color of the grass.

Despite their different background, the two experts had the same methodology. They segmented images with large zones; furthermore they chose the same zones.

EXPERIMENT 2: VISUAL SCALING WITH NAIVE OBSERVERS

With this image database, we did a psychophysical experiment with naive observers in order to collect their preference judgements.

Experimental Procedure

As the two experts had the same behaviour for enhancing images and because psychophysical experiments are time consuming, we used the images enhanced by one expert to run our experiment. We printed the images produced by the first expert on the Epson 7600 printer in one batch, including calibration charts in each printing page. The printed images were 17 cm $\times$ 26 cm. The printed sheets were presented to observers in a Gretag light booth with dimensions of 60 $\times$ 50 $\times$ 45 cm. We measured a color temperature of 5112 K with the Minolta spectrophotometer CS-1000. The average light level in the room was variable due to the presence of a window but the cabin was large enough to consider that external light had no influence on the perception of images. We worked with ten volunteer observers who were all computer scientists. They were naive to the experiment and to color image processing. There were five men and five women, between 23 and 32 years old.

Experiment

In this article, the original image is noted O and the steps of the main image corrections are called A1, A2, etc. The steps of alternative corrections are called B1, B2, etc. Other alternative corrections are called C1, C2, etc.

In order to rank the images, we used a pair comparison experiment where all the possible pairs were presented.[9] With six different versions of the same image, fifteen pairs are therefore shown in one set. We noted the six enhanced versions of one image randomly A, B, C, D, E, or F. When presented to naive observers, paired images were presented in this order: AB, AC, AD, AE, AF, BC, BD, BE, BF, CD, CE, CF, DE, DF, and EF. For each pair, we asked the observers "which image do you prefer?" They had no time constraints to answer.

In a preliminary experiment, we chose six enhanced versions of each image among the original and the five to eight versions produced by the expert. We usually eliminated the original, particularly when there was an obvious color cast that would have been rejected by observers, and we usually eliminated the first step of correction too. We kept alternative versions of corrections when available. We showed those six versions to naive observers with a paired comparison experiment described below. We used the results of this preliminary experiment as a selection procedure to include the most preferred image in our experiment. We added some images not shown in the selection test, like the first step of correction or the original image and we eliminated some versions clearly rejected by observers. Consequently, the original image was not always present in the experiment: for Garden and Lighthouse, the original was not shown because they had a strong color cast and for Buddha, we chose to test all the enhanced versions.

We performed the experiment with images selected in the preliminary experiment, using the paired comparison technique. The ten observers saw all the sets of images with three repetitions. Observers did six different sessions over ten days where they saw each time four different complete sets of images. The order of appearance of sets in one session was distributed equally.

Results: Visual Scaling of Images by Naive Observers

Naive observers generally chose their preferred image without any difficulty; it seemed to be quite an easy task. When we asked the naive observers about the criteria they used to choose images, they answered with almost no hesitation. The naives told us they fixed their attention on some precise elements in the image and ranked their importance. They indicated the natural parts such as sky, skin, and grass/tree colors to be the most important parts. They said they did not look much at parts when they did not know the original color, like the Taj Mahal.

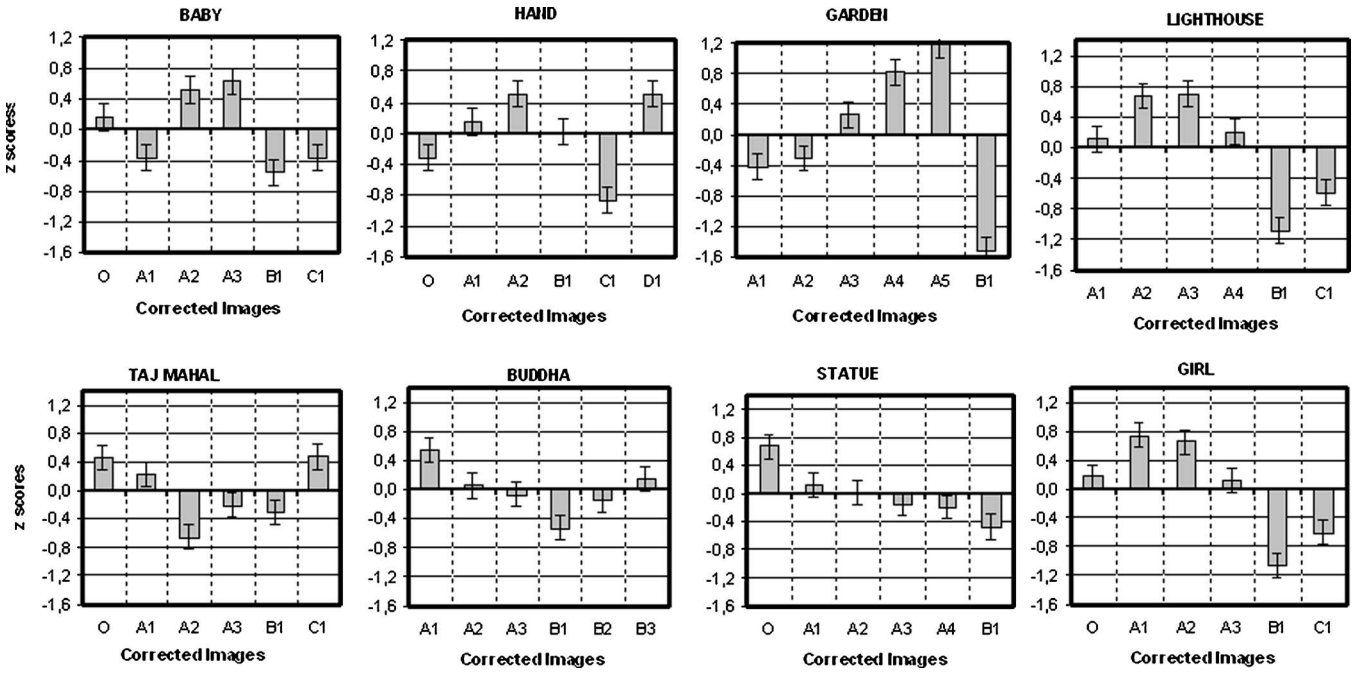

Figure 2. The *z*-scores of naive observers image preference vs expert's manipulations. Original image is called O. Steps of the main image corrections are called A1, A2, etc. Steps of alternative corrections are called B1, B2, etc. Other alternative corrections are called C1, C2, etc.

In order to rank the images according to a preference scale, we transformed the percentages of choice into *z*-scores. *Z* transformation is usually used for unidimensional factors. However, it yields to readable results with multidimensional studies as well.[1] Scales of image preference were computed following the Engeldrum's solution for Thurstone's case V solution.[9] The different *z*-scores for all images are plotted in Fig. 2 and the preference rank of each image is recalled in Table I. We added error bars to the perceptual scale data in order to assess if two samples were significantly different. It was empirically shown[10] that the standard deviation in interval scale values can be computed using the following formula where n is the number of samples, N is the number of observers and $b_1=1.76$, $b_2=-3.08$, $b_3=-0.613$, $b_4=2.55$, $b_5=-0.491$:

$$SD = b_1(n - b_2)^{b3}(N - b_4)^{b5}. \quad (1)$$

The 95% confidence interval can then be expressed as

$$CI = z \text{ score} \pm 1.96SD. \quad (2)$$

In our case $CI = z$ score $\pm 0, 17$.

When we studied the naives' preferences with the expert's manipulations, we distinguished several cases:

(i) In three images, garden, hand, and baby, naive observers preferred the final expert main correction performed after segmentation. For baby and hand, the step correction of skin tone dramatically increased the preference. For both images, the expert first changed the background of the skin and then the skin tone. She fixed the background color before focusing on the most important part of the image. Only for one image, Hand, the higher *z*-score value is obtained by a segmented version and equally by a version made with global correction. It is the only case where a global correction performed as well as a segmented correction. This alternative correction was another interpretation of the enhancement of hand image. The expert removed here global magenta color, which led to a more plausible i mage than the original. For the garden image, the five steps of correction increase a lot the preference. The changes concerned the grass, then the hose pipe color, the red of the wall, the global contrast, and the grass again. The grass was first modified as an important part of image preference, and re-modified at the end of the process to ensure that the colors were exactly the wanted ones.

(ii) In two cases, Girl and Lighthouse, naive observers preferred an intermediate version of the main enhancement made with segmentation. For Lighthouse, the preferred image was the third of the four corrections. The expert changed the image white point, the sky color, global contrast and sky, and then global contrast. The alternative correction of global contrast was rejected. For Girl, the preferred image was the first of three for the main correction. In this step, the expert changed only the skin tone of the girl's face. The second one is a little less preferred, she put white on the girl's teeth. The decrease of saturation of the background made the preference fall lower than the original image. As with the other images containing skin tones, Hand and Baby, we can notice the very important increase of preference after the correction of skin tones.

(iii) In three cases, for Taj Mahal, Buddha, and Statue,

the corrections were not chosen by naive observers. The preference decreased with manipulations. For the Taj Mahal image, an alternative correction had a higher *z* score that the original but within the error bars, so it was not significant. For Buddha and Taj, the expert told us that she chose to treat the main correction as a "travel magazine image" and the alternative correction as a "natural image." The alternative corrections were made here with segmentation. She hesitated about the right interpretation so she did both. By "travel magazine image," the expert means that she exaggerated contrast and saturation. Here, it seemed that the enhancements were rejected by observers because it seemed unreal. It is interesting to remark that, when the expert did the same psychophysical experiment as observers to scale the printed image upon her preference, she also rejected the images of the main correction for Taj and Buddha. Note that for the other six images (Baby, Girl, Lighthouse, Garden, Statue, and Hand), she preferred the final step of correction, in complete coherence with what she did while correcting the images. Here, for the three images where corrections failed, Taj, Buddha, and Statue, we can notice that they represent a scene taken in an exotic country. It is possible that both expert and naïve observers lack some references to enhance and to judge those images.

As a conclusion, the naive observers validated the expert's corrections. For five images upon eight, observers preferred an image enhanced by the expert to the original image.

QUANTITATIVE ANALYSIS OF EXPERT'S CORRECTIONS

In order to better understand the color processes that underlie the color adjustment and the color preference of images, we did a quantitative analysis of experts' corrections. We extracted color information directly from the digital image files produced by the expert.

Color Transformations from CMYK to Lab

The observers having to judge the images printed on paper, the expert produced the image in CMYK format. In order to analyze the results in a color space closer to perception, we transformed the CMYK values of the files into the corresponding $L^*a^*b^*$ values of the printed images.[11] To convert CMYK images into $L^*a^*b^*$ images, we used the ICC profile of our printer. We made this ICC profile using the IT8 characterization chart printed with our printer and we measured every patch with a spectrophotometer under the D50 illuminant. Interpolations between the colors of the patches were made using the color management module in Photoshop™. Thus, we are now working on digital images specified in the $L^*a^*b^*$ color space which represents the color prints presented to the observers.

Representation of Color Changes in Images

To understand the transformations made by the expert, we presented the color of every pixel of each image in $L^*a^*b^*$ and $u'v'$ color spaces. We plotted the colors of the pixels on two-dimension maps that are L^*a^*, L^*b^* and in $u'v'$ color planes. As the expert treated each image by dividing it into large zones in order to modify each part separately, we plotted on separated maps the pixels that belong only to one zone. The color transformations made by the expert could be represented as the move of color coordinates in a color plane. Precisely, the shift of the colors pixels between one image and its enhanced version is displayed by arrows linking the color coordinates of the original pixel (beginning of the arrow) to the coordinates of the pixels in the corrected image (head of the arrow).

Data for Memory Colors

We noticed that both experts and observers focused on natural colors like skin tones, grass or tree colors, and sky colors. These pieces of information seemed to be very important for the corrections and for the judgement of images. Experts and observers often seemed to have a precise idea of how these color areas should be. It seems that they compared the shown color to their existing internal representations. This could be linked to works on memory color from Hunt[12] or from Yendrikhovskij et al.[3] Memory colors describe those colors that are recalled in observers' memory in association with familiar objects. We analyzed the data included in the images selected by observers within the frame of memory colors. We used the previous works made by Yendrikhovkij and colleagues[3,13] and by Janssen[14] about memory colors. Yendrikhovkij did psychophysical experiments to locate areas of memory colors for skin, grass and sky in the $u'v'$ color plane. His digital images were shown on a video display. In the procedure, the colors were systematically varied in the $u'v'$ plane. Observers were asked how natural the color looked and they were invited to quantify their judgements by grading the naturalness from 0 to 10. Ratings were normalized from 0 to 1. Ellipses of memory colors were constructed so as the center of the ellipse had a score of 1 and the other points followed a Gaussian profile. The center of the ellipse is the memory color and the ellipse represents the acceptable reproduction of such color. We compared the ellipses of memory colors found by Yendrikhovskij with the data of our experiment in $u'v'$ color plane. In his experiment, Yendrikhovskij used a D65 calibrated screen. Because we did our experiments on paper under a D50 illuminant, we used the Bradford chromatic adaptation transform[15] to compute the ellipses of memory colors from D65 to D50 illuminant (Fig. 3). Recall that the D50 illuminant is intended to represent noon sky daylight and D65 the north sky average daylight. D65 is commonly used for the white point of color CRTs and D50 is more commonly used in graphic arts, because it is closer in colour temperature to typical indoor light sources used by customers to view printed products. We also transformed the coordinates of our images from $L^*a^*b^*$ to $u'v'$ using colorimetric formulas. Thus, we were able to compare the D50 transformed ellipses with our images. In order to identify the relationship between our images and memory colors areas, we plotted together the pixels of our images with the ellipses of memory colors. This allowed us to show which pixels located on image belonged to a memory color ellipse.

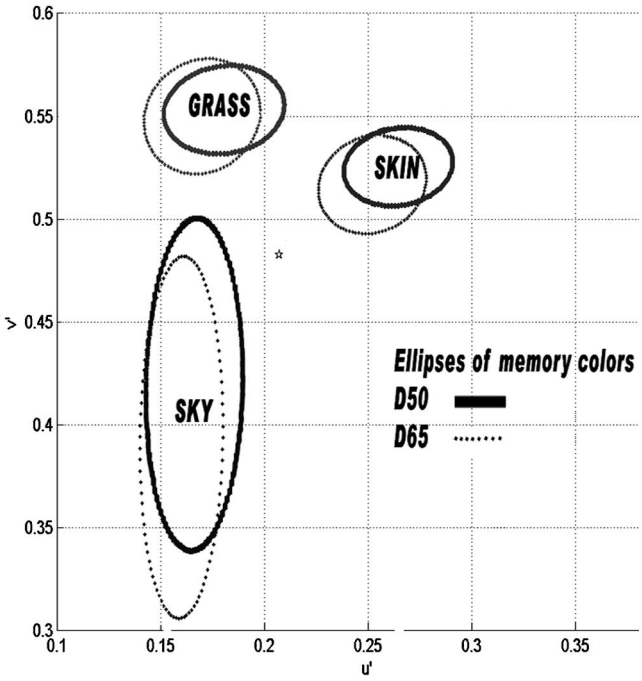

Figure 3. Ellipses of memory color areas in D50 and D65. The star point is the D50 white point.

DISCUSSION

Corrections in Lightness Planes

When the image presents a color cast, this phenomenon is particularly obvious when looking at white object in the scene. In this case, the first step of modification made by the expert is the correction of the white point of the image. This was made for Hand, Baby, and Lighthouse images that contain large areas of white objects where a color cast was obvious (respectively, paper sheet, blanket, and lighthouse). Remark that in all other images, there were no objects in the scenes that should have been white. To modify the image, the expert uses here the "set white point" tool of the "Curve" menu of Photoshop that works on CMYK pixels values. The expert selected the pixel in the image she wanted to turn white and this pixel took for example the C=M=Y=K=0 value. All others pixels in the image were automatically modified in proportion to modify the range of the pixels values of the image between this white point and the darkest point of the image that is kept unchanged. This step removed the color cast and in the same time adjusted the dynamic of the image. As Photoshop applied these transformations in the CMYK space, it had a nonlinear effect in the CIE L*a*b* space, it changed color and lightness at the same time.

Plate 2 shows all the pixels of the image Lighthouse in $u'v'$, L*a* and L*b* planes. Original image is in the upper row and the first step of correction is plotted in the bottom row. The continuous line on each diagram represents the limit of the gamut of our printer. The modifications achieved by the first step of correction and their interpretation are more obvious in lightness planes than in color plane. We can notice in L*a* and L*b* planes that the expert moved the whitest point of the original image (that is here

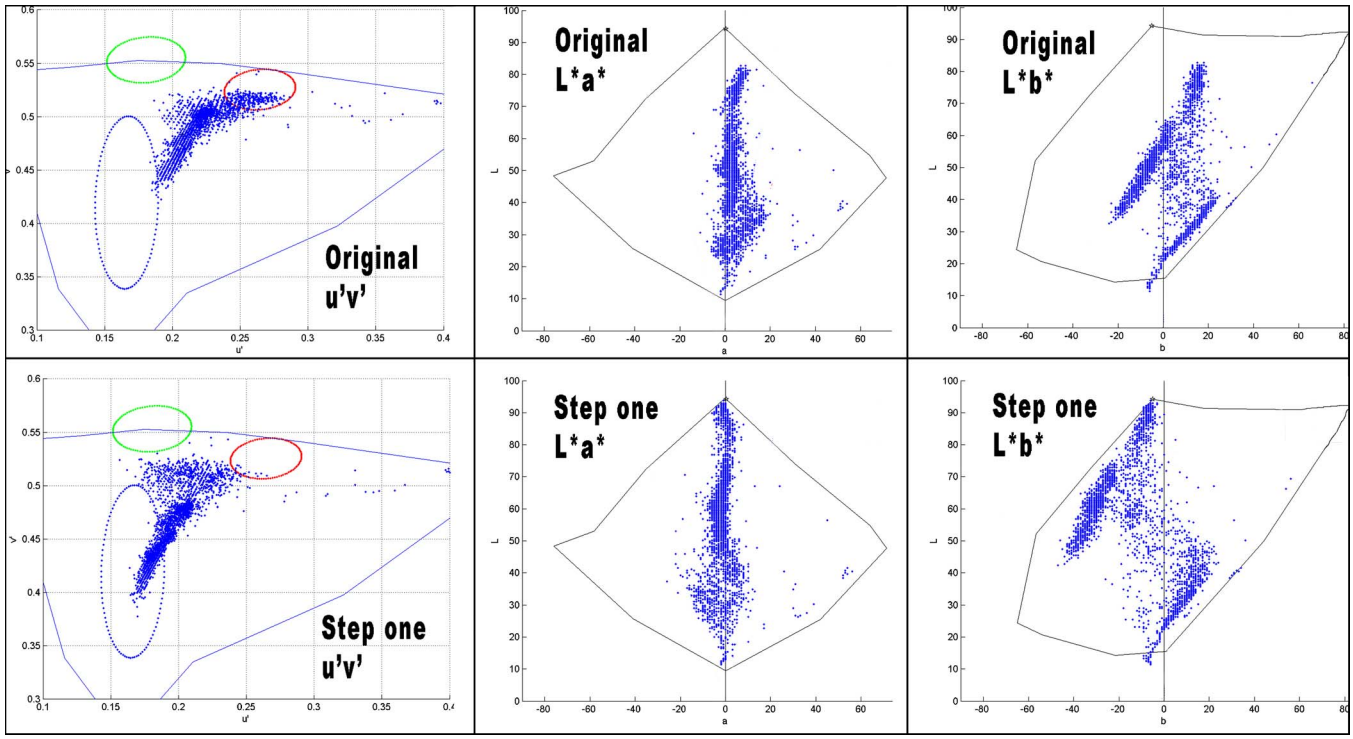

Plate 2. Lighthouse image's pixels in $u'v'$, L*a* and L*b*: original image is in the upper row and the first step of correction is on bottom. The continuous line delimits the gamut of our printer. The ellipses of memory colors are shown in the $u'v'$ column.

the white painting of the lighthouse) to the whitest point reproducible by the printer, with all the other points following. This constricted all neutral colors on the neutral axis. The original image had an obvious color cast which was removed by this first step of correction. In the L^*b^* plane, this correction led to enhance saturation of objects as groups of pixels were moving away from neutral axis and to enhance contrast as groups of pixels were moving away from each other. The colors of the pixels were now distributed to occupy the whole gamut available. The same modifications were noticed on Hand and Baby images: Moving the colors of the neutral objects to the neutral axis in $L^*a^*b^*$ space and, with less amplitude, the increasing of the contrast and saturation.

It seems that the expert tended to use the whole dynamic in lightness range and took into account the gamut available while enhancing the images. Those changes surely depended on the physical characteristics of the final receptor of the image (video display, printed paper) and the conditions of illumination during observation. More studies should be directed to the influence of those factors in our experiment.

Expert's Practice and Memory Colors

An expert firstly segmented an image in a few zones in order to enhance it. Those zones corresponded mainly to natural objects, like skin tones, grass, or sky colors. The expert changed each zone separately, and sequentially. Plotting the enhanced images in $u'v'$ plane together with memory color ellipses showed that the number of pixels belonging to memory color ellipses increased as the expert enhanced the image. Each time the expert worked on an object that could be associated with one of the three memory color locations, the colors of the pixels have moved towards the ellipses. In other words, after enhancement by the expert, more color pixels constituting the skin tones of the image belonged to the ellipse of the skin memory color defined by Yendrikhovskij.

We show here two examples. The first example is from the image lighthouse (see Plate 1). The expert used four steps to produce the image she would prefer. The step 3 image obtained the highest z-score which means that it was preferred by observers (Table I summarizes the modifications made by the expert and the preferences of naive observers characterized by z-score and rank of images). The expert first changed the white point of the image. This step changed all the colors of the image. Then she changed the color of the sky area, the contrast of the whole image and last the color of the lighthouse. In Fig. 4, we plotted the colors of the pixels belonging to the sky from image Lighthouse in the $u'v'$ plane, for each step of the main enhancement made by the expert. This figure shows that the color group of sky pixels was moving into the memory color ellipse of the sky while the expert enhanced the image. The expert made a translation and an expansion on the group of pixels to obtain the preferred image: The sky pixels now cover the whole memory color ellipse following the direction given by the white point and the center of the sky ellipse. Figure 5 shows in dark the location in image of the pixels which have their color coordinates inside the ellipse. The original image had almost no colors from the sky recognized as memory color because of it red color cast. The first step which removed the unwanted red colorcast had increased a lot the number of pixels inside the ellipse and it expanded the group of sky color pixels. Between steps 3 and 4 of enhancement, the group of colors from sky was not significantly moving in the $u'v'$ plane. Nevertheless, the observers preferred the third step of correction rather than the last step. Those two images have obtained different preference scores, which indicate that the memory colors are not the only parameter influencing preference. In all other images containing a sky part, the expert made similar corrections. Ultimately, the group of color of the sky pixels spread between the white point of the image and the most saturated point on the ellipse.

The second example is from the image Hand (see Plate 1). The expert used two steps to enhance this image. The expert changed the color of the paper around the hand and after she changed the color of the skin tone. She used the curve menu of Photoshop to adjust the skin tone color by adding some yellow. Figure 6 shows the arrows going from the colors of the original Hand image (beginning of the arrow) to the preferred one (head of the arrow) in $u'v'$ plane. The preferred image is the second and last step of the main enhancement made by the expert and is in head of the arrow. We used the mask drawn by the expert to isolate the skin tones so we only show here the pixels representing the skin tones of the image. The move of the skin pixels in $u'v'$ is characterized by the direction and the magnitude of the arrows. The arrows do not have a random behavior but have a main magnitude and direction. The magnitudes are almost the same here for all pixels. The directions are quite uniform as the group is moving toward the ellipse. However, this is not exactly a translation as the directions are slightly concentrated on one point; this leads to a compression of the group of pixels colors in the preferred image. The expert changed the colors by approaching them to the ellipse of skin memory color. The points here do not completely enter the ellipse as we will explain in next chapter, but the principle is confirmed. Corrections increased the number of points that belong to the ellipse of memory color. The location of the pixels inside the ellipse of skin memory color are represented for the original image (right up in Fig. 6) and the preferred one (right down). Pixels in dark are inside the ellipse, pixels in white are outside. Pixels in gray delimit the mask of skin tones. After enhancement, more skin colors belong to the corresponding memory color ellipse.

The relationship between the corrections made by the expert and the move of the colors of pixels towards memory color locations was verified on most images. Furthermore, as those images were preferred by naive observers, they validated the memory colors hypothesis.

Location of the Ellipses

The move of pixels in $u'v'$ plane, showed that the expert did not seem to use exactly the ellipses of Yendrikhovskij. It

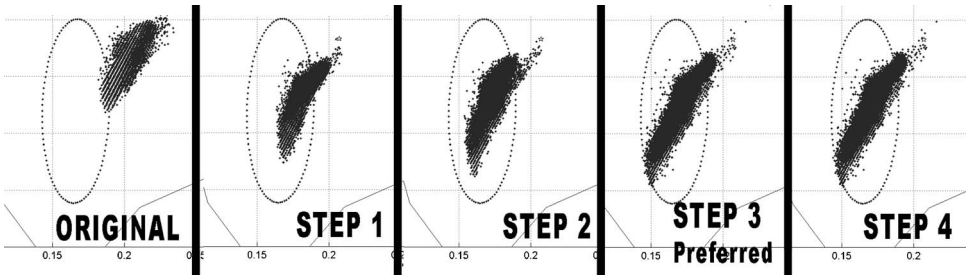

Figure 4. Image lighthouse: Colors of the sky plotted in $u'v'$ with the ellipse of memory color of the sky for the original image and the four steps of enhancement made by the expert.

Figure 5. In correlation with Fig. 4: Location on lighthouse image of the pixels having color coordinates inside the sky ellipse.

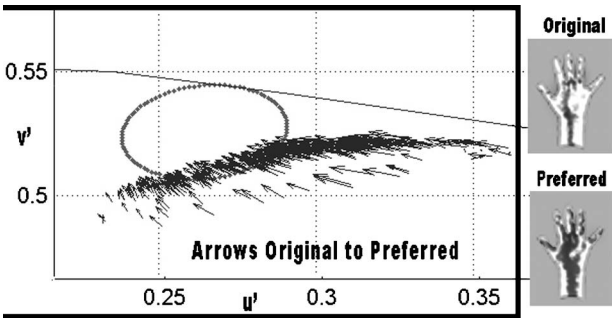

Figure 6. Hand image: Arrows from skin colors of the original image to preferred image in $u'v'$. The right column shows in dark which pixels have coordinates inside the ellipse in original (up) and preferred image (down).

seems that colors were attracted to slightly different locations. Furthermore, the gamut of the printer is limited and cannot reproduce all colors: the ellipse of grass from Yendrikhovskij is half out of the colors reproducible by the printer (see Plate 2). Questions arose about the origin of the difference between Yendrikhovskij's ellipses and the expert's ellipses. Yendrikhovskij did his experiment on a video display, with D65 white point. We used printed images viewed under D50 illuminant. The white point and the level of adaptation between the two experiments are notably different. Furthermore the two available gamuts are surely different as video display gamut is usually wider than printer gamut. Those differences could explain the difference in the location of ellipses of memory colors, as noticed by Hunt.[12] We computed the location of the ellipses for our experiment. To do so, we isolated the areas corresponding to memory colors modified by the expert on the eight images and we used images that were chosen by naive observers. We added the data from twelve new images that were corrected by the expert. We computed the average color coordinate in $u'v'$ for skin, sky, and greenery areas. Those points became the center of our new ellipses. New ellipses were constructed using the same standard deviation and covariance as Yendrikhovskij's ellipses. The newly derived ellipses could be seen as memory color areas in the mind of the expert working to enhance printed image seen under D50. Memory color ellipses from expert are plotted in Fig. 7.

We studied image enhancements by expert in relation with memory colors areas in the $u'v'$ color plane. However, memory colors areas of skin, sky, and grass have a typical range of lightness. Further analysis should be done on our images data in a three-dimensional (3D) color space including the lightness parameter of memory colors.

Directions of Corrections in Color Plane

Most of the time, the arrows representing the color shifts between two steps for the whole images in $u'v'$ plane do not make appear a single direction for all the pixels. The points move with different directions and magnitudes. For example, Fig. 8 shows the move of colors for the whole image Lighthouse between the original image and the step one of enhancement. However, when we plot a group of pixels belonging only to a segmented area drawn by the expert, the direction of this group of points becomes obvious. All the pixels of this group generally share a common direction in the $u'v'$ plane, and an organized gradient of magnitude. The moves of groups of pixels could be a translation, an expansion (especially for sky colors), or a compression (especially for skin colors) and they are usually applied to all the pixels belonging to one object. This comforts the idea that the

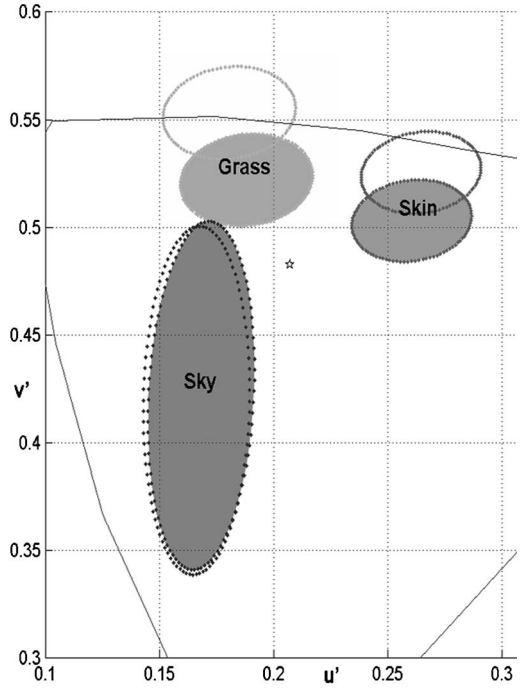

Figure 7. Ellipses used by the expert (full color) and ellipses from Yendrikhovskij (Ref. 13).

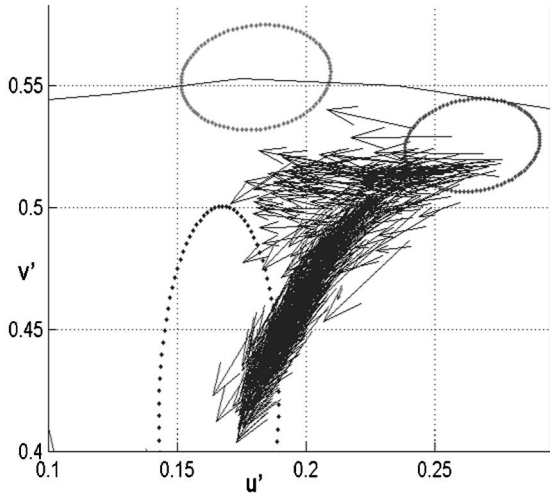

Figure 8. Lighthouse image: Changes between original and step one (head of the arrow) in $u'v'$ plane.

expert needs the segmentation process to correct each object in its own way. The expert knows the destination color she wants to achieve for a group of pixels representing a natural element.

Physical Plausibility of Image Appearance

If the association between preferred images and memory colors is clear, it is not the only criterion used by observers. Some rejected images have a high percentage of memory colors (like Lighthouse step 4). We suggest that one important element to judge an image is the coherence of the whole color distribution which should make the whole scene as natural and plausible as possible. A real world scene typically contains a single dominant lightsource (e.g., sun) that constrains the appearance of the objects in this scene.

While correcting images, the expert begins by modifying the sky when present, or the white objects that reflects the illuminant, like the blanket behind the baby's face. By doing so, we suggest that she corrects the color temperature of the illuminant. Once the illuminant is fixed, the second operation tends to adjust the color of the present objects in coherence with the chosen illuminant. The segmentations made by the expert allow to control the coherence of the whole image. The expert stops her corrections when she finds plausibility or coherence in the image, founded on her experience.

Objects themselves have physical properties that constrain the range of their possible appearance. Observers are probably able to judge the coherence and plausibility of one scene.[16] The result could be pre-known from the expert's experience in the past. As the grass gets its color from chlorophyll and has a typical spectral reflectance, not all corrections are allowed. A similar scheme shows up for skin correction. Once the expert has fixed the illuminant, either directly correcting the sky, or indirectly correcting the bed blanket, she can make the corrections within tolerances allowed by a typical healthy skin reflection. The spectral reflectance of hemoglobin is extractable from the skin reflectance.[17] The weight of this component depends upon the degree of oxygenation of the skin tissue as well as the age of the subject. We are probably well trained to the control of the color of the skin. It may be inherited from the evolution of the mankind.[18]

The idea of image coherence could be found in the color transformations of pixels. The segmentation process made by the expert allows us to correct appearance of the objects present in the scene in their own way: Different color and lightness corrections are applied to each segmented parts. The corrections represented by the transformations on groups of pixels in $u'v'$ are not anarchic and follow certain rules, constrainted by physical plausibility. For example, the whitest point of a segmented part should remain the whitest point of the group in order to keep the object plausible. For sky corrections, the expert usually changes the orientation of the group of sky pixels in order to follow the direction characterized by the image's white point, the center of the sky ellipse and the most saturated point of the ellipse. For skin pixels, the group of color is directed towards the whitest point of the image. Furthermore, the expert often applied expansion on sky color group but not on a group of skin color. Expansion of skin color group leads the observers to reject the image, probably because it seems unreal. Expert usually used color compression in $u'v'$ color planes that reflects physical phenomenon. All these transformations maintain the plausibility of each segmented part and allow to correct the whole image in coherence with an illuminant.

More research is needed to explore the relationship between the various enhancements of the images with respect to the coherent representation of the scene. Part of the procedure described in this manuscript has been previously presented in conferences.[19,20]

CONCLUSION

To enhance an image, an expert segments it into zones of interest, in order to be able to enhance each object in its own way. The zones mainly correspond to natural colors. To judge an image for preference, naive observers mainly focus on natural colors like sky, skin tones or grass when present. Both experts and naives do not focus on objects if no memory colors are associated with them. We showed that an image is preferred if the colors of the elements in the scene match the colors the observers have stored in their memory. While enhancing an image, an expert is changing the colors of the natural elements, like skin tones, grass, or sky color, to make them match the color she recalls from her memory. Likewise, naive observers clearly use memory colors to judge an image for preference. Probably, both the expert and the observers learned memory colors from elements they saw in the past, from their experiences. Furthermore, we showed that the color transformations made on image by an expert follow a few number of rules. Those transformations are constrained by physical plausibility of the appearance of objects present in the scene. We suggest that an expert first corrects the illuminant and later, the segmentation process allows to adjust zones of interest and other parts with respect to the coherence of the whole image. As the presence of memory colors is decisive for preference, the whole image must be coherent to the illuminant to be accepted.

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