Paper whiteness and its effect on perceived image quality

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Abstract

Whiteness is a commercially important characteristic of paper and board, although its perception depends on many factors that often are neglected by instrumental measurements. High whiteness improves the contrast of printed areas and increases the number of reproducible colours, but few quantitative studies have been published. In this paper, we report just-noticeable image quality difference (JND) from pair wise comparisons of images printed on paper substrate of different shades and whiteness. The JND was estimated to approximately 15 CIE whiteness, for the images and whiteness levels in this study, implying that a large substrate whiteness difference is required to get a significant visual impact on image quality. Unlike previous studies limited to colour rendering issues, the influence of the substrate's shade as a surrounding frame to the images was also investigated here. It was found that the surrounding frame did not have a significant impact on image quality, when the images had an inherent dim background around the objects in the image. However, floating images in which the image objects are adjacent to the unprinted substrate would need further attention, since their perceived image quality seemed to depend both on the colour reproduction related to whiteness and shade, and on the contrast between the image and the substrate.

Introduction

The whiteness level of paper is a commercially important quality, although the perfectly corresponding instrumental measurement remains elusive [1]. Many evaluation methods and numerous whiteness equations have been proposed over the years, of which The CIE whiteness (W_{CIE}) has gained acceptance within the paper industry. This formula is based on the CIE chromaticity coordinates, as shown in Equation 1 [2],

$$W_{\mathrm{CIE}} = Y + 800(x_{\mathrm{n}} - x) + 1700(y_{\mathrm{n}} - y) \ , \qquad (1)$$

where x and y are the CIE chromaticity coordinates, and x_{n} and y_{n} are the coordinates for the perfect diffuser in the used illumination. Ganz and Pauli [3] derived an approximation based on the $L^*a^*b^*$ colour coordinates (Equation 2),

$$W_{\mathrm{CIE}} \approx 2.41L^* - 4.45b^*(1 - 0.009(L^* - 96)) - 141.4 \ . \qquad (2)$$

Thus, high whiteness is obtained for large L^* and large negative b^* values. The CIE whiteness has been found to correlate with visual estimation of perceived whiteness for unprinted samples having similar tint or fluorescence [4]. On the other hand, the effect of paper whiteness on print quality has not been as extensively studied. Norberg [5] studied the influence of paper whiteness on perceived colour reproduction quality by performing visual assessments of printed images on papers with different CIE whiteness values. He found an improved colour rendering with increasing whiteness up to a certain level after which the paper whiteness did not have a significant impact. Coppel and Lindberg [6] studied how the perceived whiteness of unprinted areas of paper are affected by neighbouring colours. The perceived whiteness was shown to be significantly affected by simultaneous contrast effects. The perceived whiteness of unprinted patches depended on what colours were printed around. Since it is a simultaneous effect, the shade of unprinted areas of the paper would most probably influence the appearance of the printed colours too.

The present study aims at investigating the effect of paper substrate shade on printed image quality. The goal is to quantify the effect of the substrate's shade on image quality, by determining the just-noticeable image quality difference in substrate whiteness. The method proposed in this study allows separating the effect of the substrate shade as a surrounding frame to the images from the influence of the substrate on colour reproduction.

Method

The effect of substrate shade on image quality was investigated with pair wise comparisons of images printed on papers with different shades. The samples were evaluated in a perception laboratory under an overhead illumination with 5000 K correlated colour temperature. To separate the effect of the substrate's shade on the colour reproduction of the image from its influence as a surrounding frame to the image, the image pairs were evaluated with and without a frame of the paper substrate. The impact of the substrate's frame is then estimated by comparing the just-noticeable image quality difference between the two cases, and by pair wise comparison of identical images surrounded by paper substrates of different shades.

Observers were asked which image they thought had the best quality without further details. The aim is to measure how large whiteness difference is required for the group of observers to detect a difference in image quality, no matter of what different factors the observers weight in their judgment. To ensure that the different substrates only differ in whiteness, one single paper substrate was printed to different shades. Since the amount of ink printed is very low, the substrates have similar gloss and structure.

The "flower" and "champagne" ISO images (Figure 1) were chosen to study the influence of paper whiteness and shade on the perceived image quality because they contain bright areas that get strongly affected by the shade of the paper when printed. A third image, the "girl", was introduced after the first experiments. Unlike the previous images that contain an own dim background, this image is floating in a transparent background and the skin tones of the girl are in direct contact with the shade of the unprinted paper substrate. To increase the mean whiteness level, this image was evaluated under the same illumination as the other images, but with an additional UV lamp. The increase of UV amount in the illumination leads to an increase of the whiteness of the substrates (Table 1).

Samples

The samples were printed on an Epson Matte inkjet paper with a Canon BjC-8200 photo inkjet printer. The shade and whiteness was adjusted to approximate $L^*a^*b^*$ target values in Table 1. In practice, L^* was lowered by printing a gray mix of light cyan, light magenta, and yellow. Both the images and the shade of the paper substrate were printed. The printed papers were mounted on a pad of 7 copy papers to make an opaque sample . The spectral radiance factor of the printed paper substrates was measured with a Photo Research PR-650 SpectraColorimeter under the actual illuminations used in the visual evaluations, light tubes with a correlated colour temperature (CCT) of about 5000 K, or the same illumination with an additional UV lamp. The $L^*a^*b^*$ values and CIE whiteness, W_{CIE}^*, were then calculated. Note that the whiteness value was obtained under that specific illumination and white point. The star denotes that the CIE whiteness equation was applied to another illumination then the D65 illumination stipulated by the CIE.

The samples consisted of either the printed image without surrounding frame, or of the printed images in the middle of an A5 printed substrate, as shown in Figure 1 for the "Flower" image. For the pair wise evaluation, the samples with only images were mounted closed to each other on a neutral grey carton board. For the case with images surrounded by the paper substrate, the samples were mounted away from each other (~50 cm) to prevent a direct comparison of the different substrates.

In all experiments but one, the substrate was first printed at five whiteness levels, and the images were then printed on top of it. In the other experiment, conducted only with the "flower" image, the same image was printed directly on the Epson Matte paper and the paper shade was only printed around the image. Thus, only the shade of the surrounding unprinted areas was varying. The brightness of the image was first adjusted in Photoshop to make sure that no part of the image was brighter than the paper they were simulated to be printed on.

In order to restrain the number of pair wise comparisons, the samples were not compared to themselves. However, each pair of samples was evaluated left/right and right/left, resulting in 20 different pairs for each evaluation.

Three set types, consisting of 20 sample pairs each, were produced:

- Cut images without paper frame (one set with the "Flower" image, and one set with the "Champagne" image).
- Images centred on a previously printed A5 paper substrate (one set with the "Flower" image, one set with the "Champagne" image, and one set with the "Girl" image).
- Identical images surrounded by paper substrates of different shades (only with the "Flower" image).

In the first two cases, the images were different, since the same image was printed on different paper shades and no specific colour management was applied. In the last case, the images were identical for all samples, but the shade of the surrounding paper substrate was varied.

Visual evaluations

Twenty observers with no previous experience in psychophysical scaling or paper related issues participated in each experiment. All the observers scored within the average for colour discrimination in the Farnsworth-Munsell 100 hue and dichotomous tests for colour vision [7]. The sample pairs were placed on a neutral grey table in a perception laboratory with the overhead illumination used for the spectral radiance factor measurements. The sample pairs were presented in a random order for each observer. The observers were instructed to tell which of the two images they thought had the best quality.

In the evaluations where the samples consisted of images centred on a paper substrate, the observers were instructed to look at one sample at a time, and to compare the quality of the images. This instruction was added to prevent that the observers would compare the shade of the paper substrates instead of the quality of the images. The observers were also asked to tell at the end of the visual evaluation which details they were looking at when comparing the samples. A maximum of 3 observers out of 20 in each experiment reported that they saw a difference in paper shade. These observers were however not removed from the analysis presented here.

The value 0 was assigned to pairs for which an observer preferred the left sample and the value 1 was assigned to pairs for which an observer preferred the right sample. The mean response of the 20 observers was then computed to give the proportion, p, of preference judgement for each pair and the Just-Noticeable Difference (JND) was calculated with Equation 3 [8]:

$$\text{JNDs} = \frac{12}{\pi}\sin^{-1}\left(\sqrt{p}\right) - 3\,. \tag{3}$$

Table 1. *Mean L*a*b* values of the 5 printed paper substrates and corresponding CIE whiteness (W_{CIE}*), applied to spectral radiance measured under the 5000 K correlated colour temperature (CCT) illumination with and without an additional UV lamp.*

	5000 K CCT			
	L^*	a^*	b^*	W_{CIE}^*
1	95.5	-0.3	-1.3	94.0
2	90.5	0.4	-2.0	86.1
3	92.6	0.4	-2.9	94.0
4	92.5	-0.1	-4.6	100.6
5	87.6	0.5	-2.6	82.7
	5000 K CCT + UV			
	L^*	a^*	b^*	W_{CIE}^*
1	98.5	2.3	-12.7	146.0
2	97.2	2.3	-13.0	144.9
3	95.0	4.3	-15.9	148.0
4	95.0	3.6	-14.6	146.9
5	92.8	3.0	-13.9	140.2

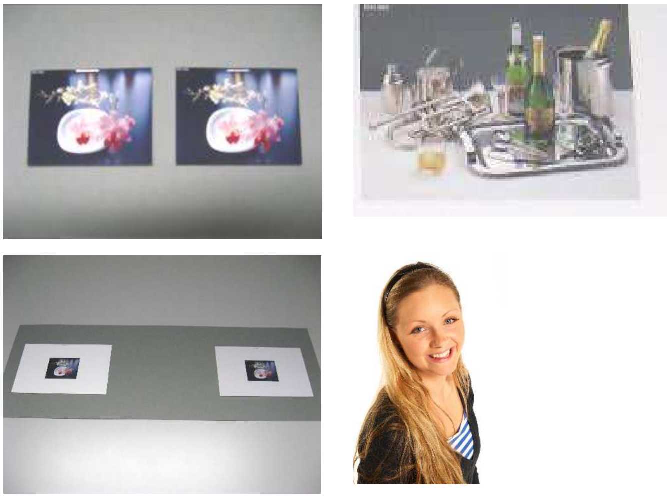

Figure 1. *Images and layout of the pair wise comparison experiments. The "flower" and "Champagne" images were evaluated both with and without a frame of the substrate surrounding the image. The "girl" image was only evaluated with the substrate frame.*

Results and discussion

Colour rendition

The JNDs are plotted Figure 2 versus the difference in CIE whiteness, $\Delta W_{CIE}*$, of the substrates, and in Figure 3 versus the difference in $L*$. For the case without a frame of unprinted substrate (Figure 2a,b) the computed JNDs correlated well with the instrumental whiteness of the substrate (R^2 = 0.8 for both the "champagne " and "flower" images). The correlation between JNDs and $L*$ was lower (Figure 3a,b). The whiteness of the substrate had a clear impact on the pair wise comparisons. The whiter the substrate the better image quality was perceived by the observers. However, the JND (JNDs = ±1 in Equation 3) corresponding to a 75% agreement between observers) was about 15 CIE whiteness for the "flower" image and about 12 for the "champagne" image. The corresponding JND in $L*$ was about 7 units for both images. Considering the commercial value of small whiteness differences, these are large differences for office papers.

In this work, the substrate was first printed to different shades and the image was then printed on top of it. Printing the nuance allowed easier production of substrates at defined nuances. Real substrates with the same $L*a*b*$ values would be bleached and dyed at various levels instead of being printed. Assuming that the small amount of ink put on the substrate before printing the images did not affect printability, the results hold nonetheless for real samples in the specific illumination used in the experiments. The method used here differs also from the study of Norberg [5] who made use of different ICC profile for each substrate. However, it reproduces real life use of office papers since no custom ICC profiles are usually used for different papers.

Effect of the substrate as a frame surrounding the image

For the case with a frame of unprinted substrate surrounding the images (Figure 2 c,d) the correlation between JNDs and substrate whiteness was much lower (R^2= 0.4), but the JND was about the same as in the case without substrate surrounding the image. The lower correlation can be partly explained by the fact that the observers did not make a direct comparison of the images but were instructed to look at one image at a time.

The correlation between JNDs and $L*$ was higher for the case with substrate surrounding the images (R^2= 0.8, Figure 3 c,d). Thus, the perceived image quality seemed to depend more on whiteness than $L*$ when the substrate shade was not seen, whereas it seemed to depend more on $L*$ when the image was surrounded by a frame of the substrate shade. This might be attributed to a greater contrast between the image and the surrounding paper substrate and would require further investigations. Nonetheless, the results suggest that the background substrate's whiteness did not have a significant effect on perceived image quality, for the flower and champagne images used in this study. This was confirmed in the experiment where the images were identical but the shade of the paper substrate frame varied. In that case, the observers did not perceive any difference between the samples (Figure 2e), meaning that in the case of perfect colour management for the image, the shade of the substrate surrounding the images did not affect the perceived image quality, for these particular images.

However, these images contain an own dim background around the objects in the images, as the plate and flowers in the "flower" image, or the bottles in the "Champagne" image. For the floating "girl" image, which was evaluated only with pairs of samples printed on paper with different shades, the correlation between JNDs and whiteness was very low, meaning that the observers did perceive any difference in image quality between images printed on paper with CIE whiteness differences up to 15 units. The correlation between the JNDs and $L*$ was slightly higher, but surprisingly negative, i.e. the observers seemed to prefer the printed images on substrates with lower $L*$. The low correlation between JND and whiteness could be a result of how the whiteness level (and thereby shade) influence the naturalness of the reproduced skin tone. The characteristics of the "girl" image differ from the others by its obvious relationship to naturalness of the skin tones. On the other hand, the low, but yet significant negative correlation between JND and $L*$ showed that the observers seemed to prefer the "girl" image with a darker background. Hence, the perceived image quality of the floating "girl" seemed to depend both on the colour reproduction related to whiteness and shade, and on the contrast between the image and the substrate.

Conclusions

When images containing bright areas are printed on paper with different whiteness without dedicated colour management, as it is the case in office printing, perceived image quality increases with increasing whiteness and correlates better with CIE whiteness than $L*$. However, large whiteness difference is required for different papers to reproduce image qualities of detectable difference.

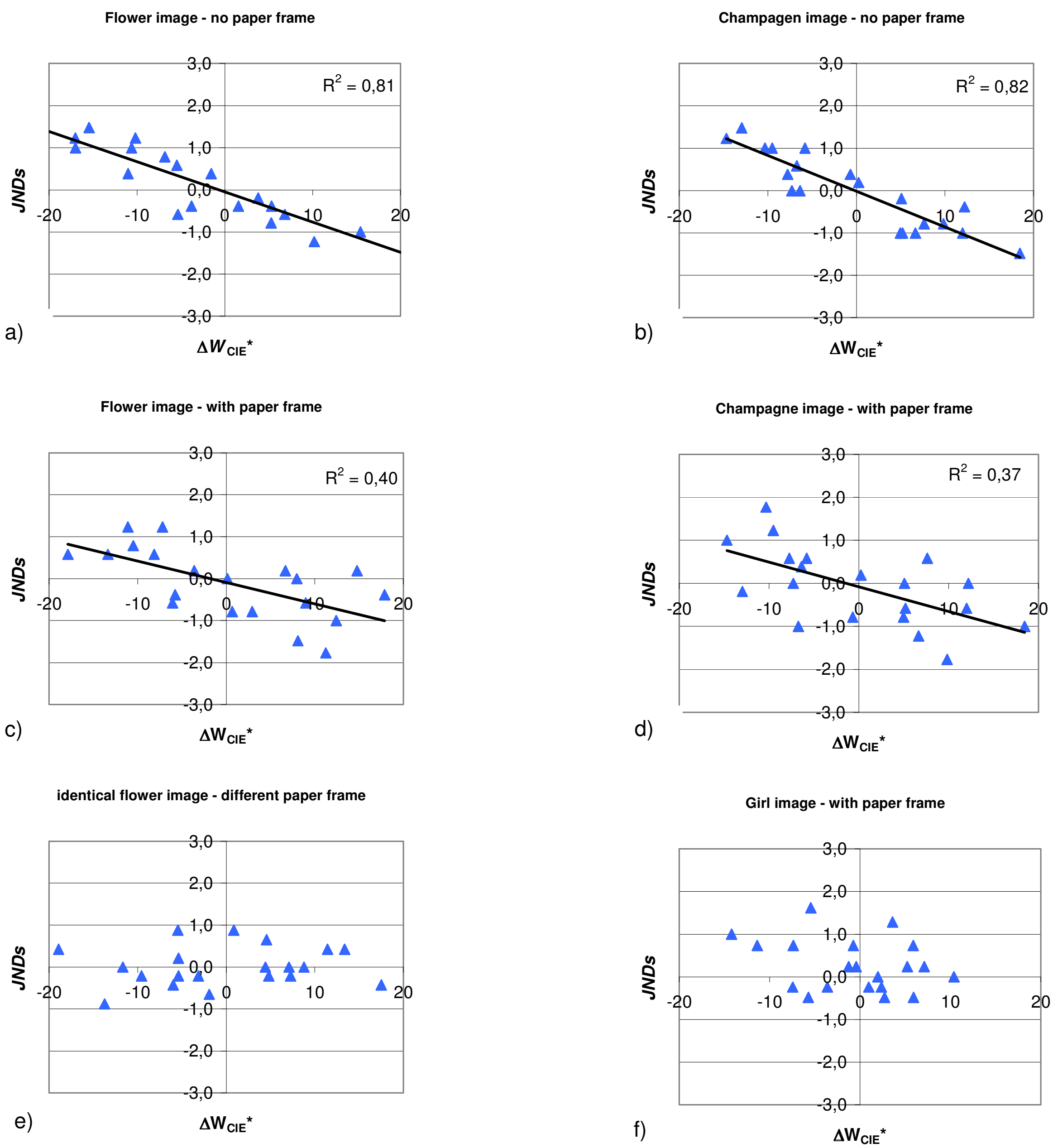

Figure 2. *JNDs versus difference in CIE whiteness applied to measurements under the overhead illumination. (a) flower image printed on different paper shades. (b) champagne image printed on different paper shades. (c-d) same as (a-b) but with paper around the images. (e) The same flower image surrounded by paper frames of different shades. f) Girl image printed on different paper shades. a-e were measured and visually evaluated under the 5000 K CCT overhead illumination, and f) under the same illumination with an additional UV lamp.*

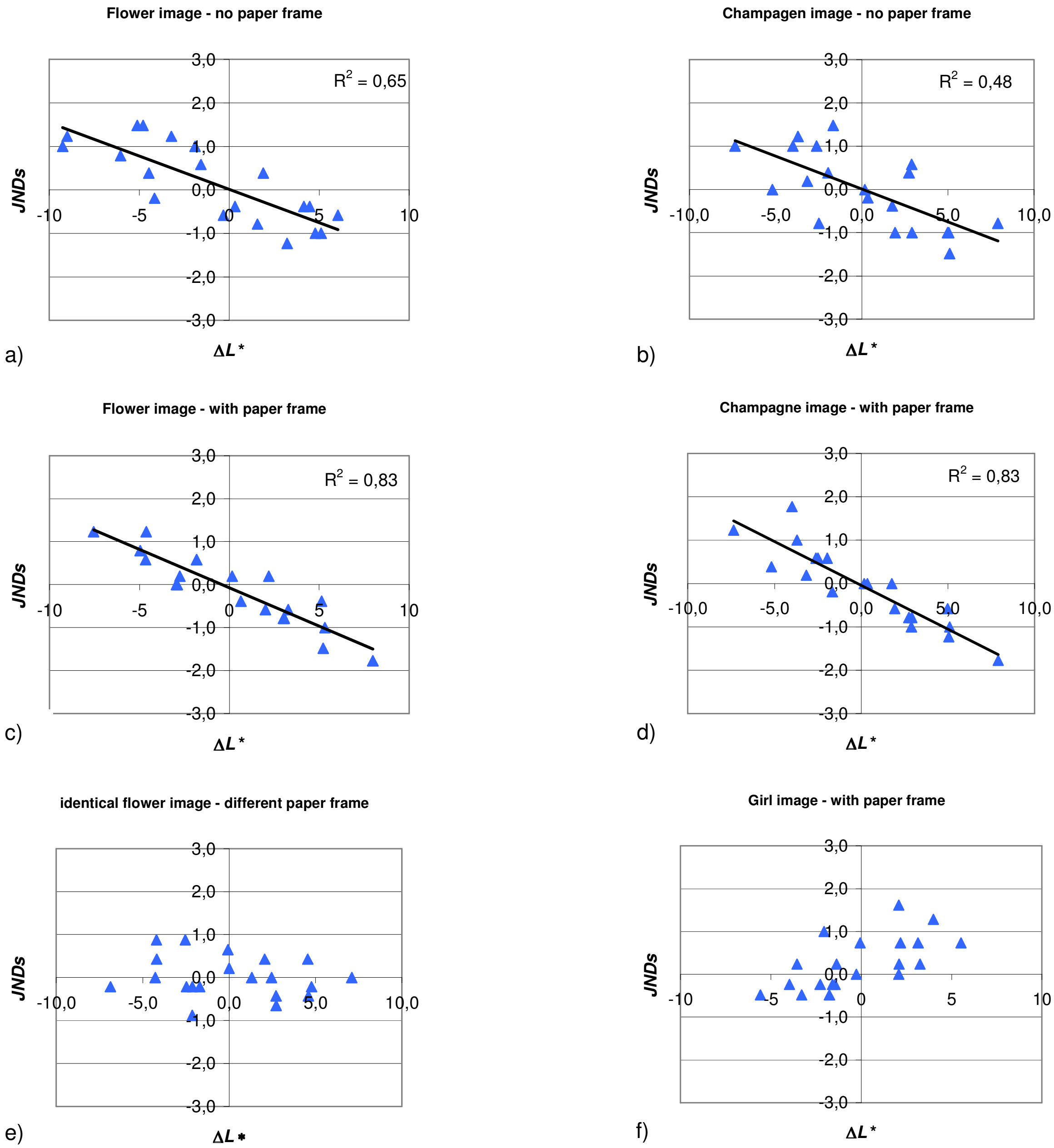

Figure 3. JNDs versus difference in L measured under the overhead illumination. (a) flower image printed on different paper shades. (b) champagne image printed on different paper shades. (c-d) same as (a-b) but with paper around the images. (e) The same flower image surrounded by paper frames of different shades. f) Girl image printed on different paper shades. a-e were measured and visually evaluated under the 5000 K CCT overhead illumination, and f) under the same illumination with an additional UV lamp.*

The shade of the unprinted substrate around the image does not have a significant impact on the perceived image quality, for images containing an own dim background, as the flower and champagne images used in this study. A potential simultaneous contrast effect between the substrate and the image was nonetheless observed for a floating image having the unprinted substrate as frame. Colour reproduction and simultaneous contrast may interact in a complex visual process affecting colour naturalness of skin tones and contrast. Further experiments should focus on different floating images to get a better understanding of the effect of the background substrate onto perceived image quality. The samples should be mounted identically in both the cases with and without paper as a frame surrounding the images, and a larger whiteness span should be used. Different whiteness levels, such as darker newsprint like shades, are also of interest.

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Author Biography

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