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# Content-dependent adaptation in a soft proof matching experiment

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## Abstract

*A 'consistent colour appearance' is hard to achieve between different substrates or display systems. A chromatic adaptation transform or substrate adjustment strategy is typically used, but for this present paper a dynamically scaled ICC Media Relative transform was utilised.*

*A soft-proofing system with a method of adjustment was used, allowing simultaneous viewing and adjustment of a reproduction colour image relative to a reference on different simulated substrates under P2 viewing conditions.*

*The degree of adjustment was found to be highly correlated to the image content's lightness and to lesser extent its chromaticity, and was not consistent with the complete adaptation assumed by a media-relative rendering.*

*Other aspects of the experimental setup, including accuracy, observer strategies, and the application of soft proofing for media relative adjustments are discussed.*

## Context

A printed image may be reproduced on a substrate that is significantly different to a standard proofing substrate, or reproduced across multiple different substrates. An interest in 'consistent colour appearance' and the problems inherent in disparate reproductions are active areas of CIE research [1].

A state of mixed or incomplete observer adaptation is at odds with graphic arts solutions that typically assume either no adaptation (an absolute colorimetric match) or full adaptation (a media-relative match). However, a subjective preference for the rendering of neutrals is known to be reliant on the luminance and chromaticity of the adapting whitepoint [2]. This may be for a substrate or an illuminant whitepoint. However, an observer preference for neutrals is also highly image dependent [3], and involves mechanisms of adaptation that are higher-level cognitive and contextual in nature, as well as lower-level physiological responses.

### Chromatic adaptation

Mechanisms of adaptation are generally classified into two groups; physiological and cognitive [4]. Physiological mechanisms include the parts of the human visual system (HVS) that are sensory in nature such as pupil dilation, overall light and dark adaptation, and chromatic adaptation. Chromatic adaptation may be seen as analogous to the channel-independent 'white balancing' of a camera, a gain control for the three types of rod receptor in the retina. A human observer may therefore see a scene under different lighting conditions but, largely by adapting to the lightsource, still perceives it as having much the same appearance.

Chromatic adaptation models (CATs) of differing complexity may be employed, but they essentially follow von Kries' hypothesis of normalising the predicted HVS cone responses relative to the adapting whitepoints of each viewing condition [4, Ch.9].

Cognitive mechanisms, or higher functions, describe those aspects of the adaptation which rely on the interpretation of visual information, including memory, preference and prior knowledge of scene content [5]. This is particularly true of scene content perceived as well recognised objects, and for which a preferred colour appearance may over-ride the prevailing viewing conditions. This aspect of the HVS is often referred to as 'cognitive discounting of the illuminant'.

### Media relative colorimetry and substrate correction for colour matching

Where a difference between substrates is modest a typical strategy for handling image colorimetry is to combine an ICC Media Relative transformation [6] (an XYZ tristimulus normalisation relative to the substrates' respective whitepoints) together with a standard blackpoint compensation [7]. The ICC Media Relative transform is functionally identical to the tristimulus correction method in 12647-2:2013 [8] that provides printers with a means to modify aim values for different papers.

The substrate correction method has been shown to help achieve conformance to aim values on differing substrates [9], particularly where low ink coverage means the substrate is more visible and contributes to greater colorimetric differences. However, further work [10] has shown this effect to exacerbate appearance mis-match in hardcopy-to-softproof comparisons where the presence of optical brightening agents (OBAs) in hardcopy substrates creates the greatest (and most noticeable) colour differences in images that are both high-key and neutral.

### Mixed and incomplete adaptation

Mainstream approaches to colour reproduction assume that an observer is completely adapted to the reproduction medium. However, for mixed viewing conditions, and particularly for prints on non-white substrates, this is rarely the case.

Previous work has quantified the state of mixed adaptation between a hard copy illuminated by room lighting and a soft copy displayed on a monitor, where the whitepoint chromaticities differed significantly [2]. An adaptation factor of between 40% and 60% for display-based images is suggested, depending of the display luminance, though the variance in observer judgements is greatly increased by high-chroma images. It is also clear that complete adaptation is less likely the more an adopted illuminant's chromaticity differs from daylight [5].

Some CATs therefore include a weighting factor for incomplete adaptation, including CAT02 [4] where the weighting factor is derived from the adapting and surround luminances.

### Adaptation to image content

A subjective preference for the rendering of neutrals is known to be reliant on the luminance and chromaticity of the adapting whitepoint. However, observer preference is also highly content dependent. Bala [3] demonstrates the sometimes inconsistent observer preferences for memory colours (such as skin-tones, landscapes, etc.), graphical elements (line art, charts, etc.), and images with large areas of neutrals. Greyscale images are also affected, with scene content shown to illicit different preferred tonings (for example, a warmer grey preferred for greyscale skin-tones).

In a grey balancing experiment Green and Otahalova [11] allowed observers to choose from grey patches of differing chromaticities at a given lightness, and to select the one that appeared most neutral. This was repeated for grey patches at different lightness levels, and on several substrates. Generally the media-relative approach was successful for light greys as they appeared neutral closer to the substrate chromaticity. However, darker greys appeared more neutral closer to an illuminant-relative chromaticity. Data fitting inferred an adapting whitepoint somewhere between the substrate colour and a perfect diffuser (i.e. a mixed adaptation that was broadly in agreement with [2]), both in terms of chromaticity and lightness.

For a print-to-display comparison Green and Oicherman [12] found that the degree of observer adaptation for a given test scene to be broadly constant when reproduced on a range of different substrate colours (including different lightness and chroma values).

In work focused on print re-targeting and on the acceptability of media-relative transforms between similar substrates, Baah et al [13] found that tolerances for lighter and more neutral tint patches were smaller than for higher chroma and darker solid patches, indicating different levels of observer adaptation relative to the reproduction substrate in each case. This pattern was repeated in both hard-copy and display presentations.

### Observer adaptation to soft proofs

Arend and Reeves [14] describe the difficulties of teasing apart the various mechanisms of adaptation; chromatic adaptation (low-level physiological response), simultaneous contrast (spatial effect), and colour constancy (cognitive/contextual, including discounting the illuminant). In an early display-based experiment analogous to soft-proofing, observers were asked to make visual adjustments based on colour-match or appearance-match criteria. As noted by Fairchild [5], the effect of different instruction was enough to enable 2 out of 3 observers to modify their on-screen visual assessments.

The observer's ability to 'discount the illuminant' of a physical print under a given light source is not well replicated on screen. Fairchild notes the effect of image content and context on adaptation to simulated scenes, giving the example of an image of a pair of hands holding a simulated print which dramatically increased observer adaptation to the display whitepoint.

## Objective

Much like the paper by Arend and Reeves [14], this experiment is designed to separate image content and the observer's preconceptions of a print matching exercise from the underlying physiological mechanisms of chromatic adaptation. The objective is to explore the effect of adaptation to image content itself rather than a predetermined media whitepoint, and to quantify that degree of adaptation. This is of significance for cross-media image adaptation, but also for print-related matching tasks that are often simulated on screen.

Results will determine the suitability of display-based tasks for delivering experimental work that might otherwise be undertaken with hardcopies, and especially for work that includes a substrate adaptation.

## Method

This section describes the software and hardware implementation, underpinning colour transformations, and viewing conditions, and also the appearance matching tasks undertaken by observers.

### Software and hardware implementation

The Matlab-based software was designed to accept source image colorimetry and transform it into an XYZ-based D50 PCS-type exchange space. Source colorimetry was scaled relative to a virtual D50 reference whitepoint and to a virtual substrate-adapted whitepoint, creating two images that were then transformed into D50 display colorimetry and RGB display values in a way that used only a fraction of the available luminance range. This allowed two images with different media whitepoints to be displayed simultaneously, with a reproduction whitepoint chroma of up to C*=30 relative to the D50 reference whitepoint without exceeding the gamut of the display (see Fig.1). As the true whitepoint of the display was not visible, the simulated media provided the adapting whitepoint(s).

For computational speed the main colour transforms (source-to-Lab, Lab-to-display, etc.) were encoded as LUTs based on pre-computed DeviceLinks, rather than using colour transforms formed of multi-element ICC profiles. This approach, however, meant that input and output parameters had to be decided upon and prepared in advance, and inevitably created some quantisation errors and artefacts within the imaging system.

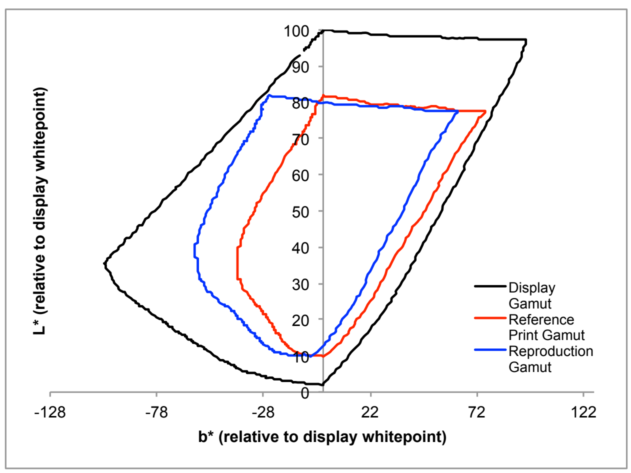


Figure 1: Gamut projection – a simulation of two substrates, defined by display colorimetry

The simulated reproduction medium gamut was a direct transform of the simulated reference medium gamut, so no gamut clipping, gamut mapping or blackpoint compensation occurred as a result of the transformation. Both media whitepoints were presented at the same luminance level, and so only an adaptation relative to the two substrate chromaticities occurred. Inevitably a few high-chroma reproduction colours still fell outside the display gamut at certain hue angles, and these were clipped by the display system when they occurred.

### Display setup and viewing condition

An Eizo CG241W 24” display was calibrated and profiled to a D50 whitepoint at 200cd/m$^2$ using ColorNavigator software and an Eye-One Spectrophotometer. The display was assessed for accuracy and uniformity in accordance with ISO 14861 [15] and ISO 12646 [16].

The D50-simulation lighting in the room was dimmed, and measured using a Minolta CS1000 telespectroradiometer. Relative to a calibration tile the luminance of a perfect reflecting diffuser at the display faceplate was less than 3cd/m$^2$, and less than 10cd/m$^2$ at a table top in front of the observer.

The reference substrate’s whitepoint was then simulated at a relative luminance of 0.6 of the display’s peak white, equivalent to 120cd/m$^2$, and in agreement with the P2 viewing condition of ISO 3664:2009 [17].

### Method of adaptation

The chosen method of adaptation was a normalisation of XYZ tristimulus image values between the two substrate white points, following the media-relative methodology in [6] and Equations 1, 2 and 3, where $X_{mw1}$ $Y_{mw1}$ $Z_{mw1}$ and $X_{mw2}$ $Y_{mw2}$ $Z_{mw2}$ are the tristimulus values of the source and destination media whites respectively, $X_1$ $Y_1$ $Z_1$ is a source image tristimulus value, and $X_2$ $Y_2$ $Z_2$ is a destination image tristimulus value.

$$X_2 = X_1(X_{mw2}/X_{mw1}) \tag{1}$$

$$Y_2 = Y_1(Y_{mw2}/Y_{mw1}) \tag{2}$$

$$Z_2 = Z_1(Z_{mw2}/Z_{mw1}) \tag{3}$$

This paper adopts the pre-print *‘degree of adaptation’* adjustment method previously used in [12] to prepare hard copies. However, since no physical printing takes place the simulation of a print on to the reproduction substrate is made using Equations 1, 2 and 3 where the two simulated printer gamuts are media-relative in nature. The combined transform is simplified into Equations 4, 5 and 6 where $X_{D50}$ $Y_{D50}$ $Z_{D50}$ is the tristimulus value of the reference substrate, $X_{mw}$ $Y_{mw}$ $Z_{mw}$ is the tristimulus value of the reproduction substrate, and $d$ is the degree of adaptation. $X_s$, $Y_s$ and $Z_s$ are the resulting scalars.

$$X_s = (X_{mw}/(X_{D50} - d(X_{D50} - X_{mw})) \tag{4}$$

$$Y_s = (Y_{mw}/(Y_{D50} - d(Y_{D50} - Y_{mw})) \tag{5}$$

$$Z_s = (Z_{mw}/(Z_{D50} - d(Z_{D50} - Z_{mw})) \tag{6}$$

A consequence of transforming print colorimetry to an adopted whitepoint other than that of the substrate colour is either that highlight detail becomes out-of-gamut and is clipped, or that a pseudo-white highlight must be printed, thus causing a reduction in overall contrast.

Since the present work is intended to look at adaptation and media-relative colorimetry only (and avoids lightness scaling and gamut mapping issues) the clipping that would normally be associated with a device profile is deliberately avoided. It is acknowledged that the adopted white inferred by an observer’s partial adaptation could not be realised in print without other gamut mapping considerations being taken into account.

### Accuracy of the softproofing system

72 patches from a standard CMYK control wedge [18] were displayed via the Matlab interface, simulating a print on the reference substrate. These were measured using the Minolta CS1000 telespectroradiometer and compared to calculated colorimetry. Measurement data included ambient light at the faceplate of the display. The strategy of using only a fraction of the available display luminance meant that not all addressable RGB values were used. However, a mean $\Delta E_{(00)}$ of 0.85 and a maximum $\Delta E_{(00)}$ of 1.85 was reported, falling well within the tolerances laid down in [15] for a soft-proofing system.

### User interface and method of adjustment

The reference and reproduction images were presented on a full-screen neutral background of relative lightness L*=50. Each image was 600 pixels (162mm) square with an additional substrate-white border of 90 pixels (24mm) (see Fig.2). Observers sat approximately 120cm from the display.

Observers were instructed to adjust the adopted whitepoint of the reproduction image using the left and right cursor keys to change the degree of adaptation in Equations 4, 5 and 6, where D of 1-$d$ = 1 created a media-relative rendering and D of 1-$d$ = 0 an absolute colorimetric rendering.

Additionally, the *increment* of adaptation could be changed (in steps of d = 0.8, 0.4, 0.2, 0.1, 0.05 or 0.025, where an increment of 0.1 roughly equates to $\Delta E_{(ab)}$of 3 or $\Delta E_{(00)}$ of 2), leaving the observer free to iterate their own visual preference (see Fig.2). The starting point was always a random degree of adaptation between the two whitepoints, and the range of adjustment given to observers significantly exceeded the limitations of $d$=0 to 1.

The degree of adaptation, the increment of adjustment and time taken was recorded automatically by the driving software.

### Observer tasks and stimuli

Test scenes and patches were prepared using ICC profiles based on the ‘SWOP coated’ characterisation data set. First-phase scenes were selected from ISO 12640 standard colour image data [19] and second-phase scenes with the appropriate Creative Common usage rights were selected from the Flickr image library [20] and prepared for print output using a perceptual rendering intent (see thumbnail images in Tables 1 and 2). The experiment was divided into three observer tasks, each of which was an exercise in appearance adjustment: similar appearance of colour scenes; similar appearance of colour patches; and a media-relative (‘print-look’) of colour scenes. A total of 16 observers (11 male, 5 female) took part in the first phase, with 13 of them returning to complete the second phase. Observers were pre-screened for colour deficiency, and a short training session ensured adaptation to the viewing environment.

In this experiment a simulated blue paper was presented next to the D50 reference white paper. Both simulated papers had the same display luminance (equal simulated print reflectance). Relative to the white reference paper the reproduction blue paper

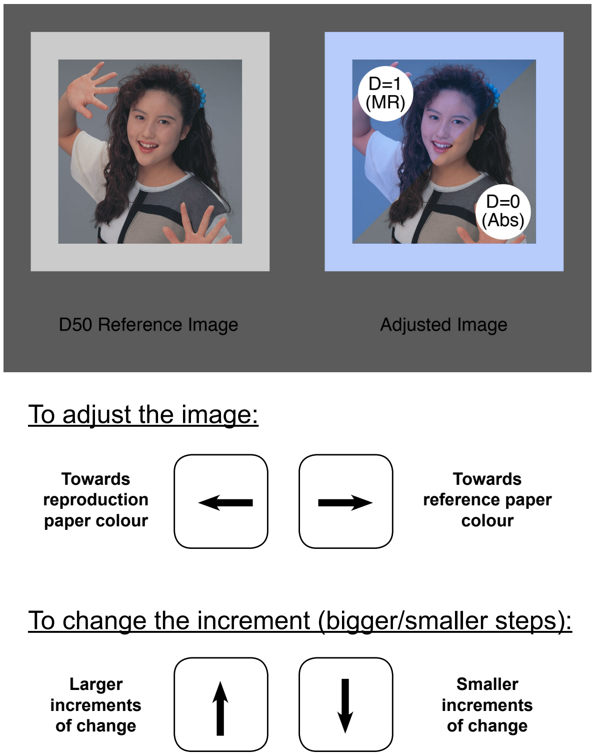


Figure 2: User interface and keyboard controls

had a colour of Lab=[100,0,-30]. The relative chroma of the blue paper is equivalent to that of publications such as the Financial Times newspaper.

### *Task 1: Similar appearance for colour scenes*

Observers were briefed using a standard script:

*Images are often printed on paper that is not plain white. A good example of this is a Financial Newspaper (actual hardcopy provided). During this experiment you will evaluate a series of images that are simulated to look as if they are printed on different papers. You will adjust the reproduction image so that it has an appearance that is as similar as possible to the reference image.*

The concept of 'similar appearance' was left for each observer to determine, though the task had clearly been set in the context of printing onto a highly coloured substrate. Observers were able to adjust the degree and increment of adaptation dynamically using the keyboard cursor keys until they arrived at something close to an appearance match.

The task was repeated for twenty three scenes (eleven in a first phase of the experiment, twelve in a second phase).

### *Task 2: Similar appearance for colour patches*

Observers repeated the first task, but with a series of twenty one colour patches (twelve in a first phase of the experiment, nine in a second phase). Again, the concept of 'similar appearance' was left for each observer to determine.

### *Task 3: Media-relative ('print-look') for colour scenes*

A modified script was provided:

*Printed on to the Blue Paper. You are now asked to imagine how the reference image would look if it were printed on the blue paper. You should adjust the reproduction image to look as though it is printed directly onto the blue paper. Hint: Usually, the lightest/whitest part of the image is close to the colour of the unprinted paper.*

Observers were offered a practice session if they were unsure of the strategy they wished to adopt. The instructions made explicit the concept of a 'media-relative' match without naming it as such, with pilot studies suggesting that the hint was appropriate for observers who did not have knowledge of graphic arts.

The eleven SCID scenes were used for this part of the experiment, and results recorded as before.

## Results

The degree of adjustment applied by observers to the simulated reproduction was recorded for a series of images in these colour appearance matching tasks.

### *Task 1 results: Similar appearance for colour scenes*

In the first task all observers adjusted the reproduction scenes to something closer to an absolute colorimetric match to the reference in response to the request for a 'similar appearance', despite the task being clearly framed as a print-on-paper problem. Only expert observers questioned whether they should take into account the blue border of the reproduction.

However, the degree of adjustment was not constant across all the stimuli. The degree of adaptation D to the reproduction substrate (where D=1 would signify complete adaptation and a media-relative rendering) ranged from just 0.04 for the Image 3 'Fruit Basket' which is a dark scene containing large high-chroma elements, to 0.27 for the Image 5 'Bicycle' which is high-key and largely neutral (see Table 1).

Inter-observer variance was calculated as a mean absolute deviation, averaging 0.13D. Lowest variance amongst the observers was for the neutral and greyscale scenes. Scenes that included a largely yellow stimulus with little or no highlight detail (Images 12, 15, 18 and 22) were problematic, and were adjusted on average with a negative D value, essentially away from the blue reproduction substrate to an adapting whitepoint even more yellow than the reference white substrate. These scenes were adjusted with a high degree of observer variance.

### *Task 2 results: Similar appearance for colour patches*

In the second task observers adjusted the reproduction patches in response to the request for a 'similar appearance'. The degree of adaptation was significantly reliant on the patch colour itself, with degrees of adaptation ranged from D = -0.10 for the darkest grey patch, to D = 0.61 for a very light neutral patch (closer to a media-relative adaptation). Only one patch was lighter (a high-chroma yellow) and which observers felt looked similar to its reference with an adaptation factor of D = 0.33 (see Table 2).

Inter-observer variance was similar to the scene-matching task, calculated as a mean absolute deviation averaging 0.13D.

## TASK 1 Results – adjust reproduction to have an appearance that is as similar as possible to reference

Degree of adjustment D (1=Reproduction substrate adapted, 0=Reference substrate adapted)

### Phase One – 11 scenes (derived from CMYK SCID Images) viewed by 16 observers

| **Image Name** | **IMAGE_01** | **IMAGE_02** | **IMAGE_03** | **IMAGE_04** | **IMAGE_05** | **IMAGE_06** | **IMAGE_07** | **IMAGE_08** | **IMAGE_09** | **IMAGE_10** | **IMAGE_11** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Image Type | Colour | Colour | Colour | Colour | Colour | Colour | Colour | Colour | Greyscale | Greyscale | Greyscale |
| **Image Statistics** | | | | | | | | | | | |
| Mean L* | 54.52 | 47.93 | 48.42 | 58.40 | 75.74 | 46.38 | 46.26 | 40.22 | 37.87 | 51.71 | 62.15 |
| Mean C* | 4.85 | 3.93 | 17.89 | 1.86 | 4.67 | 9.31 | 6.23 | 8.31 | 0.03 | 0.00 | 0.00 |
| Mean d | 0.92 | 0.91 | 0.96 | 0.82 | 0.73 | 0.83 | 0.95 | 0.90 | 0.93 | 0.88 | 0.85 |
| **Mean D (1-d)** | **0.08** | **0.09** | **0.04** | **0.18** | **0.27** | **0.17** | **0.05** | **0.10** | **0.07** | **0.12** | **0.15** |
| Mean Abs. Dev. | 0.08 | 0.17 | 0.15 | 0.12 | 0.16 | 0.13 | 0.10 | 0.13 | 0.06 | 0.07 | 0.10 |

### Phase Two – 12 scenes (derived from RGB library images) viewed by 13 observers

| **Image Name** | **IMAGE_12** | **IMAGE_13** | **IMAGE_14** | **IMAGE_15** | **IMAGE_16** | **IMAGE_17** | **IMAGE_18** | **IMAGE_19** | **IMAGE_20** | **IMAGE_21** | **IMAGE_22** | **IMAGE_23** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Image Type | Colour | Colour | Colour | Colour | Colour | Colour | Colour | Colour | Colour | Colour | Colour | Colour |
| **Image Statistics** | | | | | | | | | | | | |
| Mean L* | 67.13 | 66.47 | 64.89 | 48.30 | 72.44 | 75.41 | 66.53 | 65.03 | 93.54 | 81.93 | 52.62 | 43.94 |
| Mean C* | 51.01 | 10.23 | 29.40 | 18.73 | 5.59 | 3.18 | 39.11 | 5.40 | 0.93 | 7.65 | 15.73 | 39.55 |
| Mean d | 1.28 | 0.79 | 0.92 | 1.10 | 0.83 | 0.86 | 1.01 | 0.88 | 0.77 | 0.88 | 1.02 | 0.96 |
| **Mean D (1-d)** | **-0.28** | **0.21** | **0.08** | **-0.10** | **0.18** | **0.14** | **-0.01** | **0.12** | **0.23** | **0.12** | **-0.02** | **0.04** |
| Mean Abs. Dev. | 0.37 | 0.11 | 0.15 | 0.21 | 0.08 | 0.07 | 0.14 | 0.07 | 0.09 | 0.05 | 0.18 | 0.11 |

Phase 1 & 2 Combined Results

| | **MIN** | **MAX** | **MEAN** |
|---|---|---|---|
| Mean d | 0.73 | 1.28 | 0.91 |
| **Mean D (1-d)** | **-0.28** | **0.27** | **0.09** |
| Mean Abs. Dev. | 0.05 | 0.37 | 0.13 |

Table 1: Task One – Scenes and observer degree of adaptation

## TASK 2 Results – adjust reproduction to have an appearance that is as similar as possible to reference

Degree of adjustment D (1=Reproduction substrate adapted, 0=Reference substrate adapted)

### Phase One – 12 patches viewed by 16 observers

| **Patch Name** | **ES03** | **ES08** | **ES10** | **ES13** | **ES32** | **ES37** | **ES42** | **ES45** | **ES47** | **ES52** | **ES53** | **ES75** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CMYK Value | C50,M0,Y0,K0 | C0,M50,Y0,K0 | C0,M10,Y0,K0 | C0,M0,Y50,K0 | C50,M50,Y0,K0 | C0,M50,Y50,K0 | C50,M0,Y50,K0 | C3,M2,Y2,K0 | C25,M19,Y19,K0 | C10,M40,Y10,K0 | C10,M40,Y40,K0 | C40,M70,Y70,K0 |
| **Image Statistics** | | | | | | | | | | | | |
| Patch L* | 78.82 | 74.12 | 94.12 | 96.86 | 58.04 | 72.55 | 76.08 | 95.29 | 78.82 | 74.12 | 73.33 | 52.16 |
| Patch C* | 35.61 | 38.47 | 8.25 | 45.28 | 32.31 | 44.69 | 34.01 | 0.00 | 1.41 | 24.19 | 28.32 | 27.46 |
| Mean d | 0.76 | 0.72 | 0.41 | 0.68 | 0.94 | 0.82 | 0.88 | 0.39 | 0.64 | 0.72 | 0.82 | 0.95 |
| **Mean D (1-d)** | **0.24** | **0.28** | **0.59** | **0.33** | **0.06** | **0.18** | **0.12** | **0.61** | **0.36** | **0.28** | **0.18** | **0.05** |
| Mean Abs. Dev. | 0.11 | 0.15 | 0.15 | 0.14 | 0.10 | 0.15 | 0.11 | 0.13 | 0.11 | 0.09 | 0.09 | 0.10 |

### Phase Two – 9 patches viewed by 13 observers

| **Patch Name** | **ES04** | **ES09** | **ES14** | **ES18** | **ES20** | **ES21** | **ES22** | **ES23** | **ES76** |
|---|---|---|---|---|---|---|---|---|---|
| CMYK Value | C25,M0,Y0,K0 | C0,M25,Y0,K0 | C0,M0,Y25,K0 | C0,M0,Y0,K10 | C0,M0,Y0,K50 | C0,M0,Y0,K75 | C0,M0,Y0,K90 | C0,M0,Y0,K100 | C40,M40,Y70,K0 |
| **Image Statistics** | | | | | | | | | |
| Patch L* | 89.02 | 86.67 | 98.04 | 91.37 | 62.35 | 45.10 | 31.37 | 22.35 | 62.75 |
| Patch C* | 19.21 | 19.42 | 22.20 | 1.00 | 2.24 | 2.00 | 1.00 | 1.00 | 22.02 |
| Mean d | 0.48 | 0.60 | 0.71 | 0.51 | 0.75 | 0.88 | 0.98 | 1.10 | 0.84 |
| **Mean D (1-d)** | **0.52** | **0.40** | **0.29** | **0.49** | **0.25** | **0.12** | **0.02** | **-0.10** | **0.16** |
| Mean Abs. Dev. | 0.10 | 0.10 | 0.15 | 0.17 | 0.09 | 0.08 | 0.16 | 0.27 | 0.12 |

Phase 1 & 2 Combined Results

| | **MIN** | **MAX** | **MEAN** |
|---|---|---|---|
| Mean d | 0.39 | 1.10 | 0.74 |
| **Mean D (1-d)** | **-0.10** | **0.61** | **0.26** |
| Mean Abs. Dev. | 0.08 | 0.27 | 0.13 |

Table 2: Task Two – Patches and observer degree of adaptation

### *Task 3 results: Media-relative ('print-look') adjustment for colour scenes*

Finally, in the third task observers were asked to deliberately simulate an ink-on-paper print. This task was the hardest for observers to complete, with much higher variance in the results (see Table 3). Surprisingly, most observers created a print simulation that over-estimated the degree of adjustment required to make a media-relative reproduction (essentially making scenes more blue than they needed to be). This included observers with graphic arts backgrounds who were aware of the local adaptation effect of specular highlights (which would appear 'white' even on a high-chroma substrate).

Results are for 14 observers only: of the 16 observers in this task, two were unable to complete the print-on-paper simulation, reverting to their similar-appearance strategy of the first task.

### *Observer repeatability and integration of data across experimental phases*

In the first phase of experimental work three observers from an initial group of sixteen repeated their experiments. Repeatability for the SCID images averaged a mean absolute deviation of 0.08D (where D is the degree of adaptation between the two substrates), 0.04D at the 95% confidence interval. For the colour patches repeatability averaged a mean absolute deviation of 0.09D, 0.04D at the 95%CI.

A second phase of work was undertaken with the thirteen of the same observers. Two scenes and five patches from the first experiment were included. Repeatability for these elements was a mean absolute deviation of 0.08D, 0.02D at the 95%CI.

## Analysis and discussion

The primary objective of the research was to ascertain the impact of image content on observer adaptation, and to quantify the degree of substrate adaptation that made an appearance match in this particular use case.

### *Degree of Adjustment – Neutral Patches*

For a subset of patches that contain only achromatic colours, lightness values are compared to the degree of adaptation applied by observers to make an appearance match between reproduction and reference substrates (see Fig.3).

There is near-linear correlation between the lightness of neutral patches and the observer adjustment, with a maximum degree of adaptation being 0.61D (closer to the media-relative) for the lightest patch of L*=95. The darkest patch (L*=22) was given a mean adjustment of -0.10D, indicating an adapting whitepoint that was more yellow than the reference substrate. The correlation is highly linear for values in the range of L*=30 to L*=90.

Observer variance for the degree of adaptation (indicated by the error bars set at the 95% confidence interval) is much higher for the darkest two patches, and also for L*=91 where correlation becomes non-linear.

### *Degree of Adjustment – Neutral scenes*

For neutral scenes (a subset of test scenes whose mean pixel chroma is less than six (C*<6)) the correlation between average pixel lightness to the degree of adjustment is not as well defined as for neutral patches (see Fig.3).

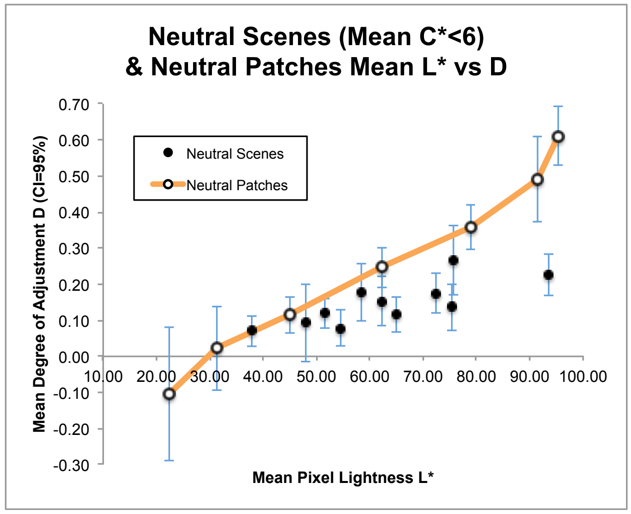


Figure 3: Degree of adjustment applied for neutral scenes and neutral patches – Tasks 1 & 2

The distribution of data shows that for all but one of the neutral scenes the degree of adaptation applied is lower than for solid neutral patches of the same average lightness.

### *Degree of Adjustment – Colour patches*

The colour patches demonstrates a general correlation between lightness and the degree of adaptation applied (see Fig.4).

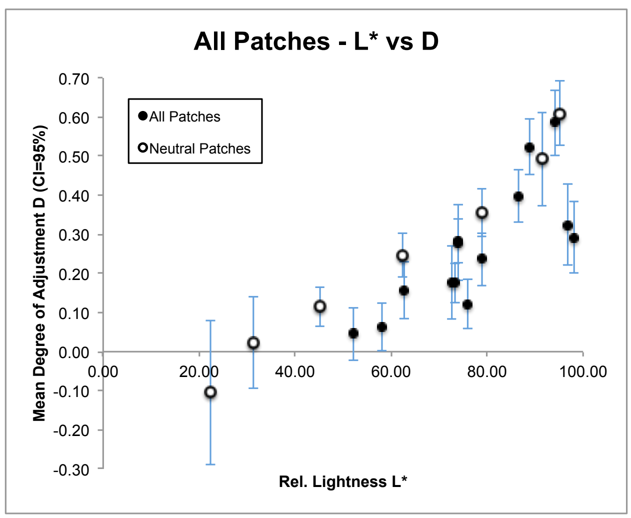


Figure 4: Degree of adjustment applied for all patches by lightness L* – Task 2

Outliers matched with lower degrees of adaptation include two very light high chroma yellow patches. Almost all colour patches were matched with a lower degree of adaptation when compared to achromatic patches of the same lightness.

The same colour patches are viewed by chroma C* in Fig.5. Achromatic patches are seen plotted close to the neutral axis adjusted in order of ascending lightness, whilst pairs of patches with similar chroma and hue attributes were adjusted with a degree of adaptation that also differed in relation to their lightness.

**TASK 3 Results – adjust reproduction to have an appearance as though it was printed on the blue paper ( a 'print look')**

Degree of adjustment D (1=Reproduction substrate adapted, 0=Reference substrate adapted)

**Image Set – 11 scenes (derived from CMYK SCID Images) viewed by 14 observers**

| **Image Name** | **IMAGE_01** | **IMAGE_02** | **IMAGE_03** | **IMAGE_04** | **IMAGE_05** | **IMAGE_06** | **IMAGE_07** | **IMAGE_08** | **IMAGE_09** | **IMAGE_10** | **IMAGE_11** | Combined Results | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Image Type | Colour | Colour | Colour | Colour | Colour | Colour | Colour | Colour | Greyscale | Greyscale | Greyscale | | | |
| **Image Statistics** | | | | | | | | | | | | | | |
| Mean L* | 54.52 | 47.93 | 48.42 | 58.40 | 75.74 | 46.38 | 46.26 | 40.22 | 37.87 | 51.71 | 62.15 | | | |
| Mean C* | 4.85 | 3.93 | 17.89 | 1.86 | 4.67 | 9.31 | 6.23 | 8.31 | 0.03 | 0.00 | 0.00 | **MIN** | **MAX** | **MEAN** |
| Mean d | -0.24 | -0.11 | -0.17 | -0.06 | -0.08 | 0.08 | 0.04 | -0.06 | -0.16 | -0.18 | -0.16 | -0.24 | 0.08 | -0.10 |
| **Mean D (1-d)** | **1.24** | **1.11** | **1.17** | **1.06** | **1.08** | **0.92** | **0.96** | **1.06** | **1.16** | **1.18** | **1.16** | **0.92** | **1.24** | **1.10** |
| Mean Abs. Dev. | 0.18 | 0.19 | 0.34 | 0.16 | 0.15 | 0.24 | 0.37 | 0.23 | 0.27 | 0.13 | 0.10 | 0.10 | 0.37 | 0.21 |

Table 3: Task Three – Print simulation –Scenes and observer degree of adaptation

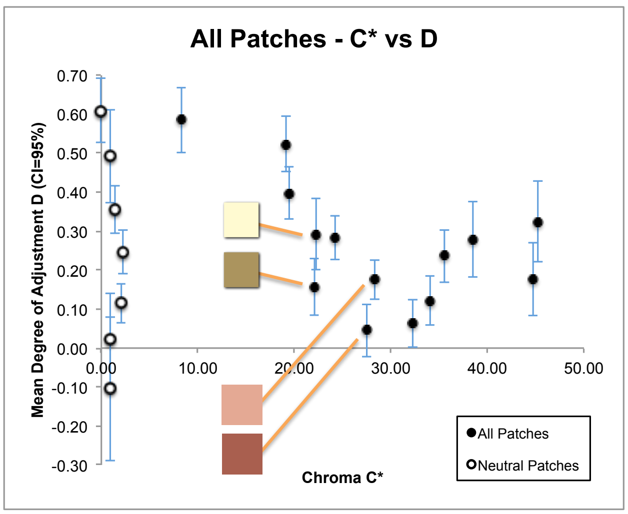


Figure 5: Degree of adjustment applied for all patches by chroma C* (patch-pairs of similar hue and chroma are illustrated) – Task 2

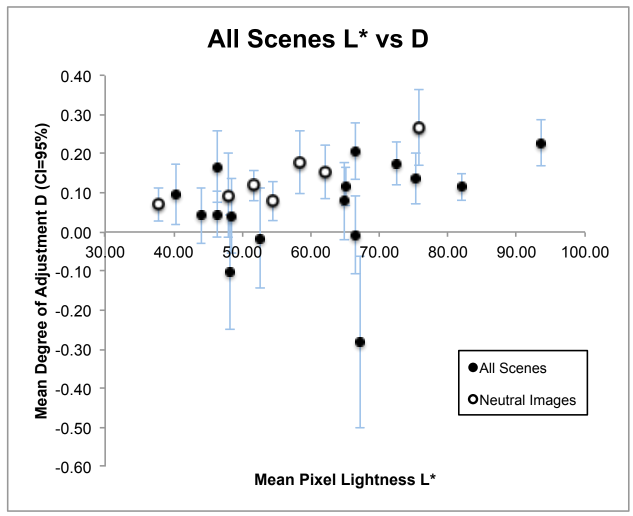


Figure 6: Degree of adjustment for all scenes by lightness L* – Task 1

## *Degree of Adjustment – Colour scenes*

The adaptation applied to all colour scenes shows only weak correlation to average pixel lightness, with lighter scenes requiring a slightly greater degree of adaptation (see Fig.6). The same colour scenes are viewed by chroma C* (see Fig. 7). High chroma scenes were adjusted with less adaptation to the reproduction substrate than neutral scenes.

## *Observer behaviour and feedback*

During phase one each observer was asked to verbally identify and comment upon areas of reference within each SCID image, and most observers adopted similar strategies (see Table 4).

Observers often picked large low frequency areas with which to make comparison between the reference and reproduction scenes, particularly of neutral greys where available. Specular highlights or open white areas (such as the tabletops in the 'Cafeteria' scene) were also closely considered.

Dominant high-chroma objects were also referenced when grey areas were unavailable. In the 'Fruit Bowl' scene often just one or two objects were chosen, though there was no consistent strategy or selection by observers.

Skintones and facial regions were consistently referred to in the colour scenes, but also in the greyscale 'Bride' scene. The sky area of the 'cafeteria' scene was also referenced. These insights show that memory colours play a strong role in substrate adaptation matching tasks, and are consistent with observations in [3].

The strong correlation between scene lightness and degree of adjustment was demonstrated when matching Image 4 'Wine & Tableware'. The scene presented two dominant grey areas, a lighter foreground area and a darker background area. As observers adjusted the degree of adaptation relative to the substrates they could make a visual match to one area only, whilst causing a mis-match in the other.

## *Appearance considerations and limitations of chromatic adaptation methods*

Normalisation of all on-screen content to a single adapting whitepoint is the preferred method for mixed content on a single display, and an LMS cone-space based transform would be better suited for that application [21].

However, chromatic adaptation models should not be expected to predict perfect appearance matches. There is evidence of a general mismatch between model-predicted and observer-matched colorimetry in [21], and it was the case during this experiment where some observer adjustments were reported as 'difficult' or 'not quite matching'. The Matlab software could therefore be

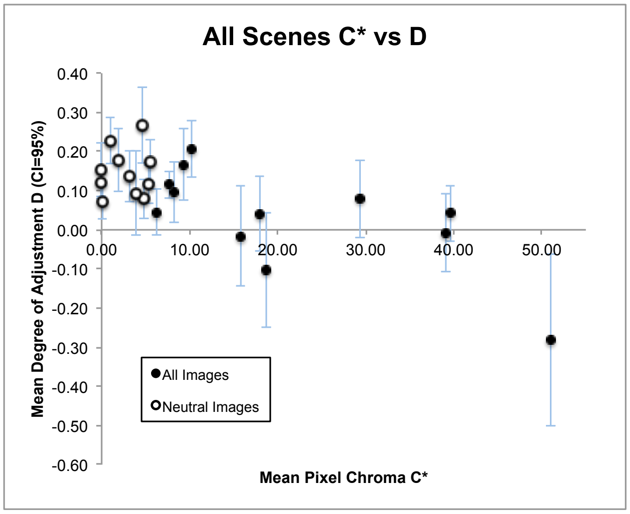

Figure 7: Degree of adjustment applied for all scenes by chroma C*

| Ref. Scene | Area of interest |
|---|---|
| IM01 Portrait | Face and skintones, grey background, white shirt-sleeve |
| IM02 Cafeteria | Sky, White tabletops, sky blue area, signage and light building fascades |
| IM03 Fruit Basket | No common areas, observer tended to pick a reference fruit or object. Background was rarely chosen. |
| IM04 Wine & Tableware | Mainly the grey foreground or background. Somethings a specific object of silverware or glassware. |
| IM05 Bicycle | Mainly the background. Occasionally the ColorChecker or a specific object. |
| IM06 Orchid | White plate, occasionally the flower. |
| IM07 Musicians | Face and skintones. Clothing and head-dress detail, predominantly left-hand figure |
| IM08 Candle | Highlight, low-frequency neutral areas |
| IM09 Glass | Specular highlights, textured glassware |
| IM10 Cafeteria | White building fascade, white boat, sky area |
| IM11 Bride | Face, white hat |

Table 4: Observer feedback – Reference areas within scenes

improved by the addition of fine-adjustment controls to give a better visual match, and produce data that does not rely on any one chromatic adaptation methodology.

### *Adaptation problems when soft-proofing mixed substrates*

Results showed that when observers were free to make an appearance match between scenes or patches on the two simulated substrates they did not chose a rendering that agreed with a media-relative transform.

Furthermore, several observers noted that they were ignoring, or trying to discount, the unprinted substrate border around each image, essentially 'windowing' the salient pixels on the display.

In the third task observers were asked to deliberately create a reproduction based on their understanding of a print-appearance (where matching the unprinted highlight areas to the unprinted border would be equivalent to a media-relative rendering). The exercise relied upon a conceptual understanding of ink-on-paper appearance rather than a physiological adaptation to the substrate colour, and this became somewhat task-driven rather than visual in nature. Two out of sixteen observers failed to understand the task, and other observers, including those from a graphic arts background, tended to over-adapt the reproduction. Their strategy of matching specular highlights to the substrate colour over-rode any local adaptation that would normally create 'white' highlights.

The conclusion is that display-based soft proofing does not lend itself to print approval or adjustment tasks that involve a change of substrate.

## Conclusions

Analysis of the results demonstrates strong correlation between image lightness and the degree of adaptation used to render an appearance match to a reproduction substrate in a soft-proof matching experiment. An adaptation closer to a media-relative rendering provided the best reproduction for lighter content, whereas a near-absolute colorimetric match to the reference was applied to match very dark images. A similar correlation was found between the colourfulness of the content and the degree of adaptation that provided the best appearance match, whereby a higher degree of substrate adaptation gave the best reproduction for neutral content, but an adjustment closer to an absolute colorimetric rendering created an appearance match for high-chroma content.

For on-screen viewing the observer's state of chromatic adaptation is modified by image content itself, in addition to the state of adaptation that would be expected by standard soft-proofing viewing conditions.

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## Author Biography

*Gregory High has his background is graphic arts, and he has worked on a wide range of commercial print projects in design studios and advertising agencies.*

*He completed his MSc Digital Colour Imaging in 2008 at the London College of Communication, and has since been responsible for colour management, proofing, pre-media and training within design and production companies. He is a member of the UK's TC-130 technical advisory group.*

*Gregory joined the ColourLab at NTNU in Gjøvik, Norway in November 2015, and the topic of his PhD research project is 'A model of consistent colour appearance'.*

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