Impact of UV content of illumination on acceptability of colour reproduction

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Abstract

Paper and board for printing commonly contains optical brightening agents that fluoresce in the presence of UV radiation, making the prints appear brighter and bluer. If the relative amount of optical brightening agents (OBAs) is not consistent between proof and print, and the UV content of measurement and the viewing illumination differs, there will be a colorimetric difference between proof and print. Colour management workflows are normally media-relative, and visual adaptation to the media white can conflict with the goals of colorimetric matching. The impact of UV content in measurement and viewing illumination on the visual acceptability of colour reproductions was investigated in a series of psychophysical experiments, using substrates with varying OBA concentrations and a media-relative colour reproduction workflow. The results showed that visual acceptability was largely unaffected by UV content of measurement or viewing illumination, suggesting that visual adaptation to media white discounts the effect of fluorescence.

Keywords

optical brightening agents, colour reproduction, colour matching, media-relative colorimetry

1. Introduction

For consistency in colour reproduction, D50 has long been the standard illuminant in graphic arts colorimetry and proof viewing. Prior to 2009, the spectral power from 300nm to the beginning of the measurement range at around 380nm was loosely defined. This led to difficulties in colour matching, since the great majority of printed substrates contain optical brightening agents (OBAs) also known as fluorescent whitening agents that cause energy in the UV region to be re-emitted in the visible, such that the spectral reflectance depends on the relative amount of UV energy emitted by the lamps used in the spectrophotometer and in the viewing cabinet.

The graphic arts measurement and viewing standards, ISO 13655 [1] and ISO 3664 [2], were revised in 2009 to provide a more rigorous definition of UV with associated tolerances for manufacturers of measurement instruments and viewing cabinets. Conditions M1 (exact spectral power as in CIE D50 from 300nm) and M2 (UV excluded) were defined, together with M0 (undefined spectral power, but in practice most commonly associated with tungsten lamps).

This approach made it possible to consistently match the CIELAB L*, a* and b* values between proof and print. However, where the proof and print substrates contained different OBA concentrations, this was at the cost of printing blue or yellow on the unprinted substrate to align the chromaticities of the white points. This tended to lead to dissatisfaction with the end result, particularly when the print was viewed or evaluated in end use conditions or office environments rather than professional viewing cabinet.

The more recent adoption of LED lamps in lighting systems has exacerbated the problem, since the widely used blue-pumped white LEDs emit significant amounts of UV, leading to greater mis-matches between end use viewing and the ISO 3664-compliant viewing booth.

An important principle in colour management is scaling the white point colorimetry so that the match is media-relative rather than strictly colorimetric, and it is well established that this gives more

CVCS2024: the 12th Colour and Visual Computing Symposium, September 5–6, 2024, Gjøvik, Norway
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pleasing results. The primary reason is that the visual system tends to adapt to the media white point, regardless of its colorimetry.

In an attempt to mitigate the mis-matches in colour reproduction, it has recently been proposed to introduce a D50noUV condition in a revised ISO 3664. This would match the spectral power of D50 only within the visible range, and suppress UV energy outside this range.

In order to investigate the issue further and determine how significant the effect of UV content are in measurement and viewing, a series of psychophysical experiments were performed on the acceptability of colour reproductions when different combinations of measurement and viewing conditions are used, and using substrates with a wide range of OBA concentration.

A study by Changlong et al. [3] investigated the perceptibility of colour differences in colour pairs due to OBAs variations in paper substrates and their correlation with quantitative measurement metrics. The research revealed that the presence of OBAs in printed colours can result in a range from imperceptible to noticeable differences. Additionally, the study found no significant correlation between illumination levels and visual color differences.

In an other study [4], a similar approach was used to assess the influence of OBAs on the characterization process. Here, two methods were employed to reduce UV content in the substrate, aiming to mitigate the effects of OBAs and differences between measurement and viewing illuminants. Another investigation examined the influence of OBAs on the stability of inkjet printer prints by assessing their effect on perceived brightness [5]. This study demonstrated that yellow ink pigment, which predominantly exhibits OBA effects, is correlated with lower ink density. Furthermore, research by Chovancova et al. [6] found that higher ink density on OBA-treated paper leads to diminished spectral reflectance under different illuminations. As a result, black solids show minimal reflection and exhibit a colour difference of zero in this context.

In previous research, various methodologies have been developed to estimate the UV content of illumination sources and to measure and model paper fluorescence for enhanced colorimetric characterization of printing processes. For instance, Green and Chang [7] proposed a technique for estimating the power of a source within the fluorescent excitation region based on the measurements of emitted flux. Additionally, Gill [8] conducted a study focused on measuring and modeling paper fluorescence to achieve improved colorimetric characterization in printing processes.

2. Methodology

A comprehensive psychophysical investigation was undertaken to assess the impact of OBAs on the acceptability of colour matching. The methodology employed for this assessment utilised a six-point categorical judgment scale, enabling a nuanced evaluation of perceived differences. The experimental design considered two main variables: the illuminant and the substrate. The substrate was especially significant, as it constituted the primary source of ultraviolet (UV) content influencing the colour reproduction process. This study aims to provide deeper insights into how OBAs affect visual perception under varying lighting conditions, contributing to the broader understanding of colour science and its applications in printing and imaging technologies.

2.1. Illumination

For our experiment, we selected viewing illuminations with different levels of UV presence. At NTNU in Norway, we conducted the visual experiment in three distinct viewing environments. Additionally, we used two viewing conditions in the Netherlands (NL):

- Combined Office and Daylight, NTNU (referred to here as: ’Off+Day (NTNU)’)
- Daylight only at noon, NTNU (’Daylight (NTNU)’)
- D50 simulator, NTNU (’D50 (NTNU)’)
- D50 simulator No-UV, Netherlands (’D50 No-UV (NL)’)
- D50 simulator with-UV, Netherlands (’D50 with-UV (NL)’)

Table 1
Normalised tristimulus values XYZ, xy-coordinates and reported CIEb* values of the reference substrates under three viewing conditions

Viewing	Substrate	X	Y	Z	x	y	CIEb*
Daylight (NTNU)	Ultra	92.906	100.000	100.455	0.317	0.341	-8.98
Daylight (NTNU)	Alpine	92.967	100.000	96.925	0.321	0.345	-7.79
Daylight (NTNU)	Filter	92.359	100.000	88.128	0.329	0.357	-3.07
Off+Day (NTNU)	Ultra	95.124	100.000	90.192	0.352	0.371	-4.92
Off+Day (NTNU)	Alpine	94.946	100.000	90.700	0.354	0.373	-5.25
Off+Day (NTNU)	Filter	94.542	100.000	84.340	0.360	0.380	-1.20
D50 (NTNU)	Ultra	94.818	100.000	74.695	0.333	0.351	6.93
D50 (NTNU)	Alpine	94.839	100.000	73.386	0.332	0.350	8.15
D50 (NTNU)	Filter	94.741	100.000	68.198	0.339	0.359	13.13

The visual experiments at NTNU, which included three distinct viewing conditions, were conducted in one of the laboratory facilities. The room is equipped with windows that can either allow daylight to enter or exclude it using sun blades. Additionally, the lab features adjustable ceiling illumination (combination of fluorescent tubes OSRAM L 58W/950 and tungsten light) with an adjustable colour temperature ranging from approximately 2800K to 5000K. This setup enabled the simulation of three viewing conditions: 'natural daylight only at noon,' 'combined office and daylight', and 'D50 simulator' exclusively. For each viewing condition, the room's illumination intensity was calibrated to the ISO 3664 standard, specifically the P2 settings, at 500 lux, using a Konica-Minolta CL-200A chroma meter.

A further phase of the experiment was performed in the Netherlands using D50 simulator illuminants with and without UV in a standard light booth. The illumination intensity in the light booth was set according to the ISO 3664 standard, with P2 settings at 500 lux, and the self-luminous white point of the screen was 160cd/m2.

To ensure the consistency of UV levels in the viewing environment over time, three reference substrates 'Ultra', 'Alpine' and 'Filter' containing different amounts of OBA [9][10] were measured under 'Daylight (NTNU)', 'D50 (NTNU)' and 'Off+Day (NTNU)' condition prior to each participant commencing the visual experiment. The resulting spectral power distributions are shown in Figure 6, normalised to 100 at 560nm. It can be seen that the 'Daylight (NTNU)' viewing condition incorporates significantly more UV energy in comparison to the 'D50 (NTNU)' and 'Off+Day (NTNU)' conditions. This observation is confirmed by the calculated tristimulus values XYZ based on the reference substrate measurements. The high 'Z' value for the reference substrate 'Ultra' under 'Daylight (NTNU)', when UV is greater, as shown in Table 1, further supports this. In addition, the visual impact of the UV content in illumination can be estimated, in particularly focusing on the corresponding CIEb* changes.

2.2. Substrate selection and measurement mode

We chose four commercial substrates from diverse families, each with varying levels of OBAs. These families comprised paper, 'Yupo', 'Textile', 'Hexis vynil', and 'Blockout PP'. The quantity of OBAs present is indicated by the white point measurement of each substrate under M1 and M2 measurement conditions, as shown in Table 2. Additionally, Figure 1 presents the spectral reflectances of the four substrates measured under both M0, M1 and M2 modes. As observed, the substrates 'Textile,' 'Hexis,' and 'Blockout,' when measured under M1 mode, exhibit a fluorescence peak around 437nm, enhancing brightness and imparting a slight bluish tint to the paper. The extent of this fluorescence depends on the amount of UV present during both the excitation and viewing of the paper. Chaikovsky and Garrison (2012) [11] compared paper samples with different levels of OBAs to those without OBAs, testing them under various lighting conditions (A, D50, and D65). They found that under D65 lighting (with the highest UV component), the blue part of the spectrum showed the highest reflectance, while Illuminant A (without UV) resulted in the lowest reflectance. This suggests that OBAs enhance reflectance in the

Table 2
White point in CIELAB of the substrates measured with M1 and M2 measurement conditions

Substrate	White point M1	White point M2
Textile	L* 87.52; a* 6.87; b* -22.13;	L* 86.76; a* 2.10; b* -5.73
Hexis vynil	L* 92.12; a* 3.89; b* -13.68;	L* 91.63; a* 0.85; b* -2.64;
Blockout PP	L* 92.22; a* 3.11; b* -12.61;	L* 91.85; a* -0.41; b* -1.44;
Yupo paper	L* 97.57; a* -0.11; b* 2.44;	L* 97.57; a* -0.13; b* 2.47;

blue spectrum under D65 lighting.

In contrast, the M2 measurement mode suppresses the UV radiation. The degree of this fluorescence is influenced by the amount of UV in the excitation region in both measurement and viewing of the paper. For substrates without any OBAs, such as 'Yupo', the choice of measurement mode does not affect the reading.

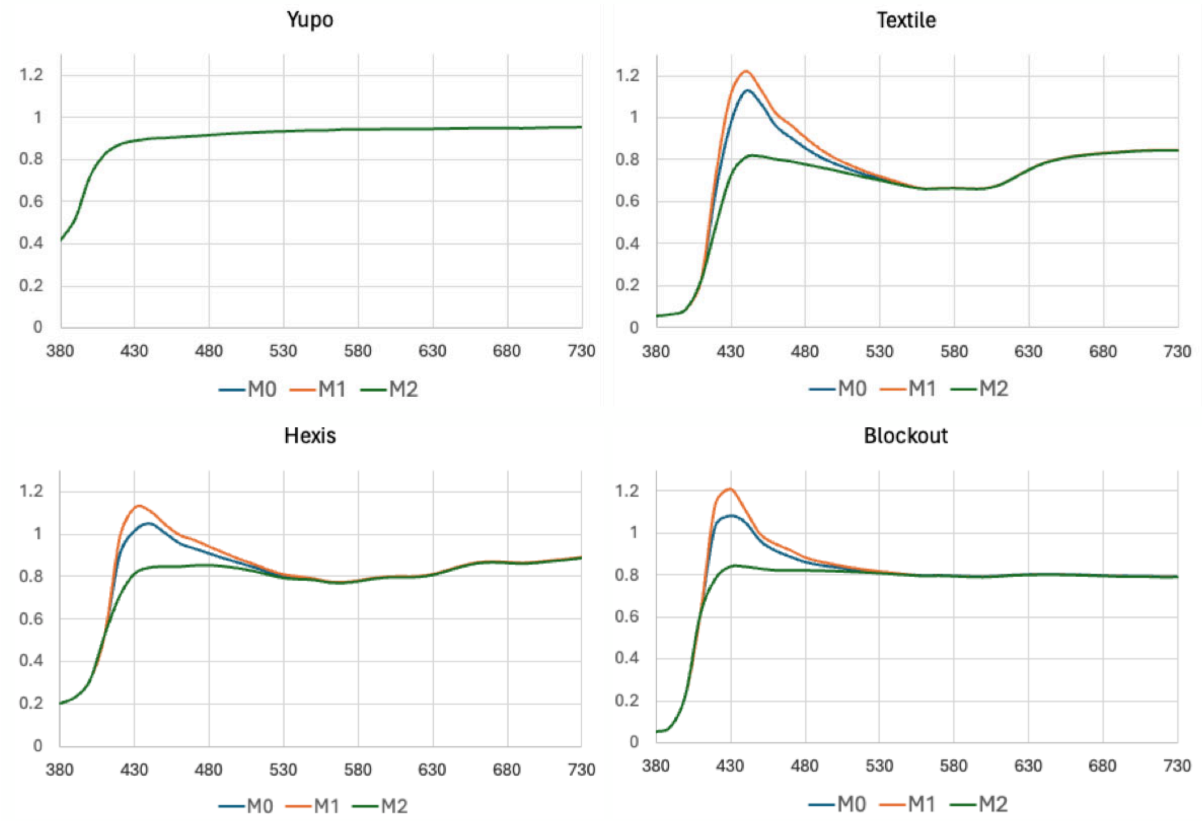

Figure 1: Spectral reflectances of the four substrates 'Yupo', 'Textile', 'Hexis' and 'Blockout', respectively, measured with measurement mode M0, M1 and M2.

The specification ISO 13655:2017 provides four different measurement modes M0, M1, M2, and M3. The correlated colour temperature of the illuminant defined in the M0 measurement condition does not define the UV information [1][12]. The measurement condition M1 is intended to match colours when the viewing booth also has D50 illumination (ISO 3664:2009). At the same time, the M2 measurement condition suppresses UV outside the visible spectrum. The measurement condition M3 shares the same sample illumination requirements as M2, but it also includes a linear polarizer to minimize the impact of first-surface reflection on the color coordinates.

In our experiment to create an ICC profile, we printed an ECI2002 characterization chart [13] on each of the four substrates and measured it with both M1 and M2 and the resulting reflectances are shown in Figure 1.

2.3. Creating intermediate UV condition

A supplementary measurement condition was calculated to define an intermediate level of UV content between M1 and M2. This intermediate condition, termed "M1.5", was derived by linearly interpolating spectral reflectances between M1 and M2 measurements.

As a result, three ICC printer profiles were created using the characterisation data M1, M2, and M1.5 for each of the four substrates.

2.4. Reference image and hard-copy samples

In the experiment, we utilised five distinct sets of CMYK standard colour image data (CMYK/SCID) sourced from the ISO standard ISO 12640-1:1997 [14], which encompassed natural scenes, as depicted in Figure 2.

Figure 2: CMYK standard colour image data (CMYK/SCID).

The CMYK/SCID images N1A Portrait, N3A Fruit Basket, N4A Wine and Tableware, N5A Bicycle, and N6A Orchid were printed on the Latex560 printer using previously created ICC profiles with measurement modes M1, M2, and M1.5, respectively. The untagged CMYK/SCID images were assigned with standard CMYK encoding and converted to the destination colour space of the four target substrates using media relative rendering intent including black point compensation. Then, the five target images were printed onto each of the four substrates. Each substrate has three measurement modes (M1, M2, and M1.5) resulting in a total of 60 printed images.

2.5. Experimental setup

The reference image was presented on a calibrated display, with a display white point corresponding to D50, a luminance level of 160.00 cd/m2, and a Gamma value of 2.2. To visualize the target images on the display, the original CMYK/SCID images were reassigned with a standard CMYK profile (ISO Coated v2 (ECI)) and a soft-proof was created using the destination colour space of the four target substrates, including the display option to simulate paper colour. Positioned in front of the display was the corresponding printed hard-copy. Subsequently, observers were tasked with assessing the visual coherence between the two stimuli, as shown in Figure 3.

While the display calibration remained consistent, the visual experiment was conducted under three distinct viewing environments at NTNU and two distinct environments in the Netherlands. At NTNU, these environmental changes were continuously monitored and verified using a Konica-Minolta CS2000A telespectroradiometer.

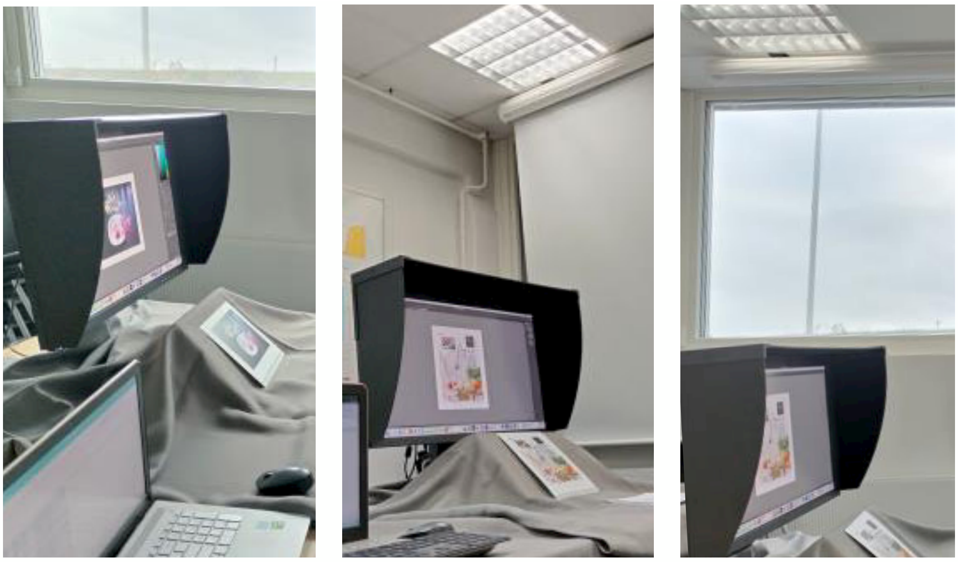

Figure 3: Experimental setup at NTNU laboratory including reference image on the display and the corresponding printed hard-copy under three distinct viewing conditions; 'Daylight (NTNU)' (left), 'D50 (NTNU)' (middle), and 'Off+Day (NTNU)' (right), (images taken by Nafia Akter).

2.6. Participants

The visual experiments were conducted in both Norway and the Netherlands. A total of 31 participants took part in each stage of the experiment, 16 in the Netherlands and 15 in Norway. The participants, who varied in age (22-60 years) and nationality, included both novice and experienced observers in colour perception. Intra-observer and inter-observer repeatability tests were conducted with each participant to evaluate the consistency of their responses over time and the results are shown in Table 3.

2.7. Experimental task

Participants were instructed to visually compare printed samples to a reference image displayed on a screen and to provide a categorical assessment of the acceptability of the reproduction. Each observer conducted the experiment under different viewing conditions: three distinct environments were utilized for observers at NTNU, while two viewing environments were used for those in the Netherlands. Prior to the start of the experiment, participants received training samples to familiarize themselves with the task and the judgment criteria. Subsequently, reference images were displayed on a calibrated screen positioned at a 45-degree angle next to the printed samples (as depicted in Figure 3), and participants were asked to assess the differences using a scoring system. For each distinct viewing condition, the experiment was repeated and prior to the experiment the observers could visually adapt to the new viewing environment.

The categorical scale reflected the perceptible difference from the reference image on the display and the corresponding hard-copy and served as an indicator of the acceptability threshold. The scale ranged from:

- 1 - Not perceptibly different
- 2 - Barely perceptible difference (but acceptable)
- 3 - Perceptible difference but acceptable
- 4 - Barely acceptable difference
- 5 - Barely unacceptable difference
- 6 - Unacceptable difference

We transformed the mean opinion score (MOS), which represents the average category score, into a Z-score, reflecting how many standard deviations a data point deviates from the mean of the distribution.

Typically, a mean opinion score is used to capture the average subjective rating provided by participants for a particular item. In our study, this involved evaluating the visual difference between the reference image displayed on the screen and the physical reproduction on the substrate. For instance, if participants rated the acceptable difference on a scale from 1 to 6, where 1 signifies "Not perceptibly different" and 6 indicates "Unacceptable difference," the MOS would be the average of these ratings.

Overall, we received responses from fifteen observers in Norway and sixteen in the Netherlands, who assessed five images on four substrates with three colour encoding across five different viewing environments.

3. Results and discussion

The effect of different levels of UV in the viewing illumination on the visual acceptability of colour reproductions on papers with different degrees of OBAs was investigated. Five viewing conditions (three at NTNU and two in the Netherlands (NL)), four paper substrates, three measurement modes (M1, M2, and M1,5), and five test images were used to investigate how fluctuations in UV radiation influence the acceptability of colour matching between soft-proofs and prints.

3.1. Inter-observer and intra-observer repeatability

Inter-observer and intra-observer repeatability were estimated during the experiments, which involved five distinct viewing conditions. Under each condition, three hard copies of different CMYK/SCID images were assessed using three measurement modes. Each assessment was repeated twice to ensure accurate estimations of repeatability across different observers and within the same observer.

Table 3 presents the mean and standard deviation (SD) values for the inter- and intra-observer repeatability. A lower SD indicates that the values are close to the mean (less variability), while a higher SD indicates more spread-out values (greater variability). Since the ratings are on a scale of 1 to 6, an SD of approximately ±1.00 suggests that most ratings are within 1.00 points of the mean rating. Given that the scale range is 5 points (from 1 to 6), an SD of 1.00 reflects a reasonable level of agreement among observers (inter-observer repeatability).

The intra-observer repeatability was slightly lower, suggesting that individual observers are more consistent with themselves than with each other.

Table 3
Mean and standard deviation (SD) for inter- and intra-observer repeatability under five viewing conditions

Viewing:	D50 No-UV NL	D50 with-UV NL	Daylight NTNU	Off+Day NTNU	D50 NTNU
Observer:	Inter - Intra	Inter - Intra	Inter - Intra	Inter - Intra	Inter - Intra
Mean	0.92 - 0.73	1.04 - 1.04	1.25 - 1.10	1.33 - 0.99	1.04 - 1.17
SD	0.99 - 0.88	1.05 - 1.06	1.16 - 1.09	1.19 - 1.03	1.05 - 1.12

The results of the psychophysical experiment predicting perceptible difference using categorical scale resulted in a frequency matrix from which Z-scores were calculated. The obtained Z-scores reflect the relative positioning of data points compared to the mean and standard deviation of the dataset. The error bars are set at the 95% confidence interval.

The Figure 5 shows the Z-scores for all five images (N1A, and N3A-N6A), colour-encoded according to measurement modes M1, M1.5, and M2, were evaluated on four different substrate properties under five dissimilar viewing conditions.

Below we review the effect of the different variables in the study.

3.2. Effect of substrate properties

Four types of substrates have been used in the experiment containing different amount of OBA's. As expected, the substrate without any OBA ('Yupo') does not effect the appearance significantly under any viewing conditions, with or without UV radiation. Although the 'Textile' substrate shows moderately higher Z-scores, we can observe that neither the measurement modes (M1, M1.5, and M2) nor the five different viewing conditions significantly affected the observers' judgments. Additionally, the three viewing conditions containing UV radiation (e.g., 'Daylight (NTNU)' or 'D50 with-UV (NL)') didn't impact the appearance compared to non-UV radiation viewing conditions.

Analyzing the data for a single image (e.g. N1A) reveals that while viewing conditions containing UV radiation have some effect on the acceptability of reproduction the different substrates used have a considerably greater effect than the viewing conditions.

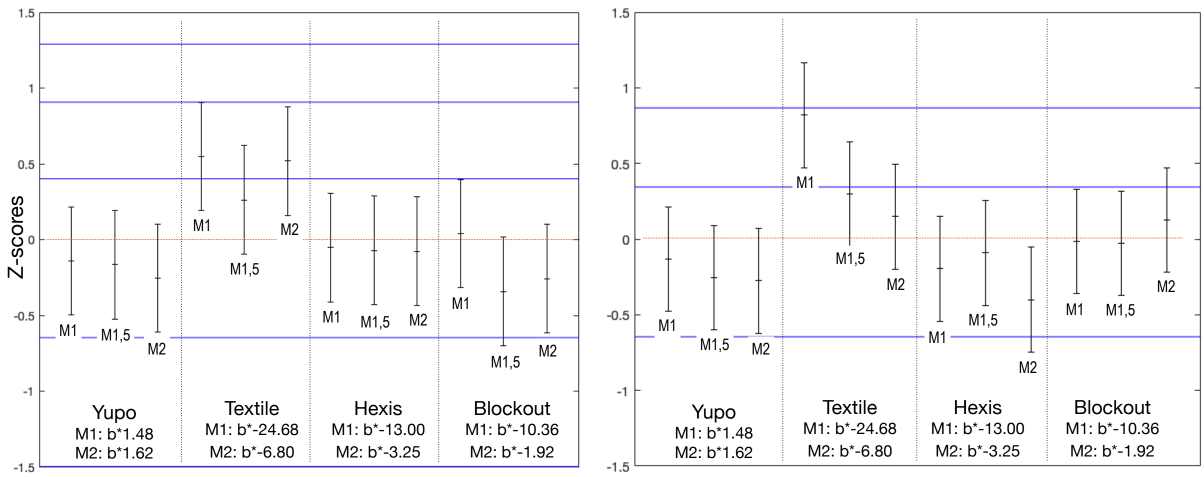

Figure 4: Test image N1A and viewing condition 'Daylight (NTNU)' to the left and viewing conditions 'D50 with-UV (NL)' to the right.

3.3. Influence of measurement mode

As can be seen in Figure 5, the measurement conditions (M1, M1.5, and M2) have minimal or no effect on substrates without OBAs. However, the M2 mode suppresses fluorescence of the substrate regardless of the OBA amount. Except for the viewing condition 'D50 with-UV (NL)', (see Figure 4), the measurement conditions do not significantly influence the acceptability of reproduction between the reference and the hard-copy. Similarly, the intermediate measurement condition 'M1.5' did not show a significant impact on the acceptability of colour reproduction.

3.4. Effect of viewing conditions

While the NTNU viewing condition 'Daylight (NTNU)' include significant amounts of UV (as shown in Figure 6), the results presented in Figure 7 indicate that neither the image content, the presence of UV in

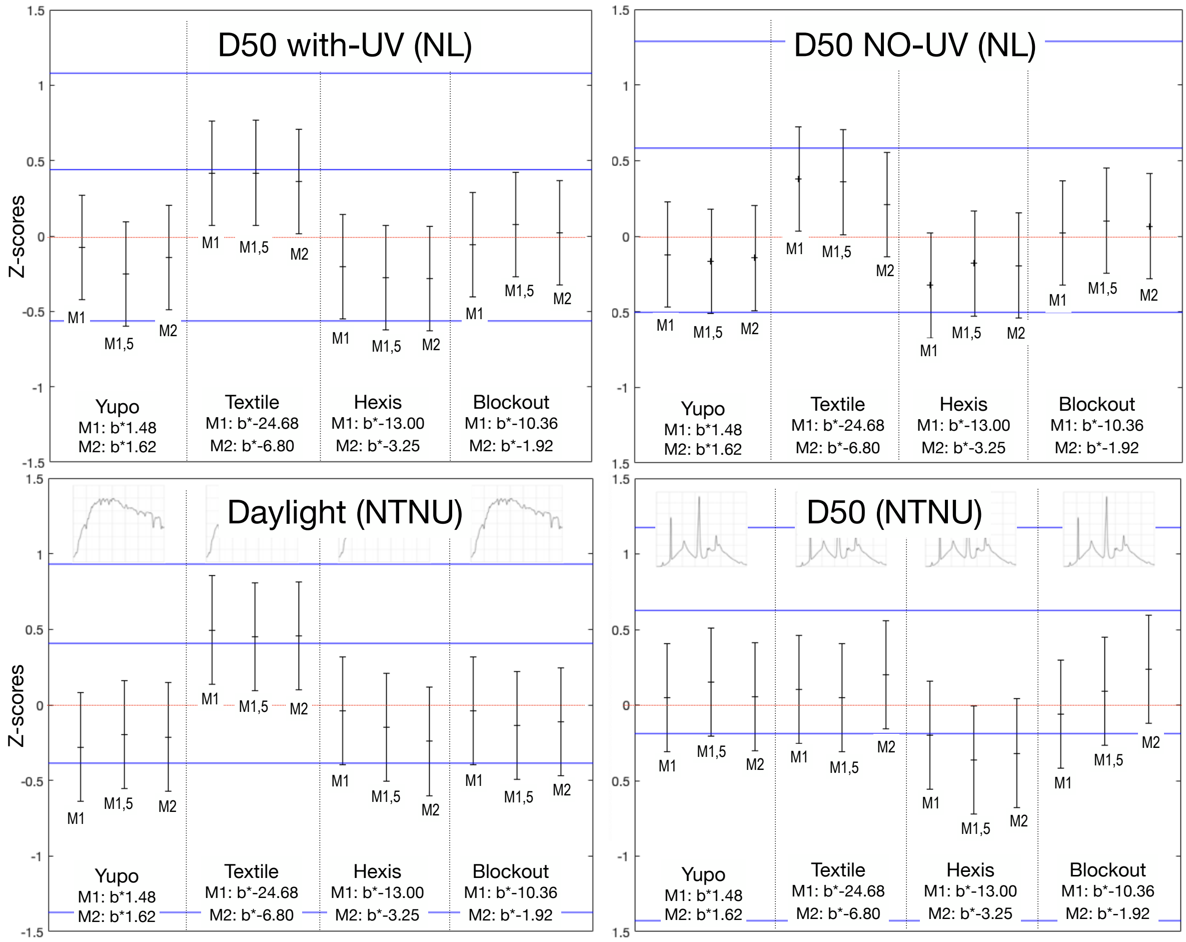

Figure 5: Z-scores for all images (N1A and N3A-N6A), colour-encoded according to measurement modes M1, M1.5, and M2, were evaluated on four substrates under four viewing conditions: top left - 'D50 with-UV (NL)', top right - 'D50 No-UV (NL)', bottom left - 'Daylight (NTNU)', and bottom right - 'D50 (NTNU)'.

the viewing conditions, nor the presence of OBA in the substrates, significantly influence the judgment between the reference on the display and the hard-copy. The viewing condition 'Off+Day (NTNU)' also did not show a significant impact on the acceptability of colour matching between soft-proofs and prints.

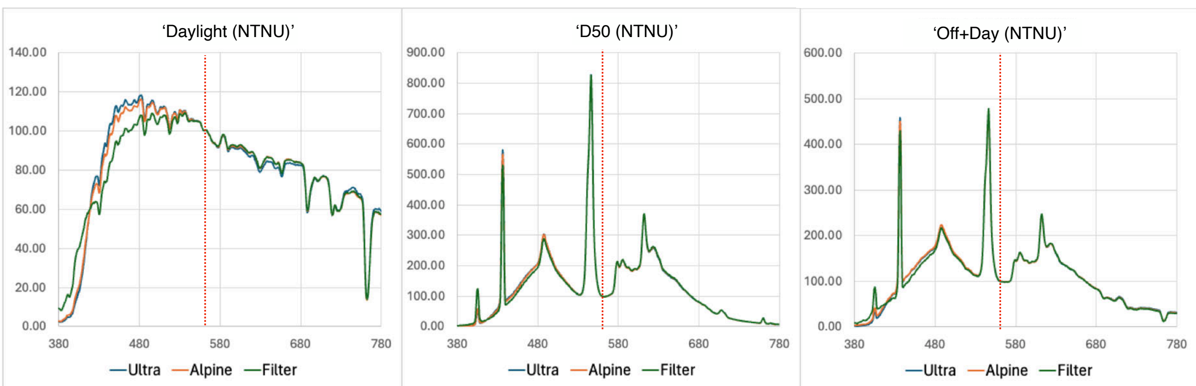

Figure 6: NTNU viewing conditions, 'Daylight (NTNU)' (left), 'D50 (NTNU)' (middle) and 'Off+Day (NTNU)' (right) and reference substrates Ultra, Alpine and Filter measured and normalized at 560nm.

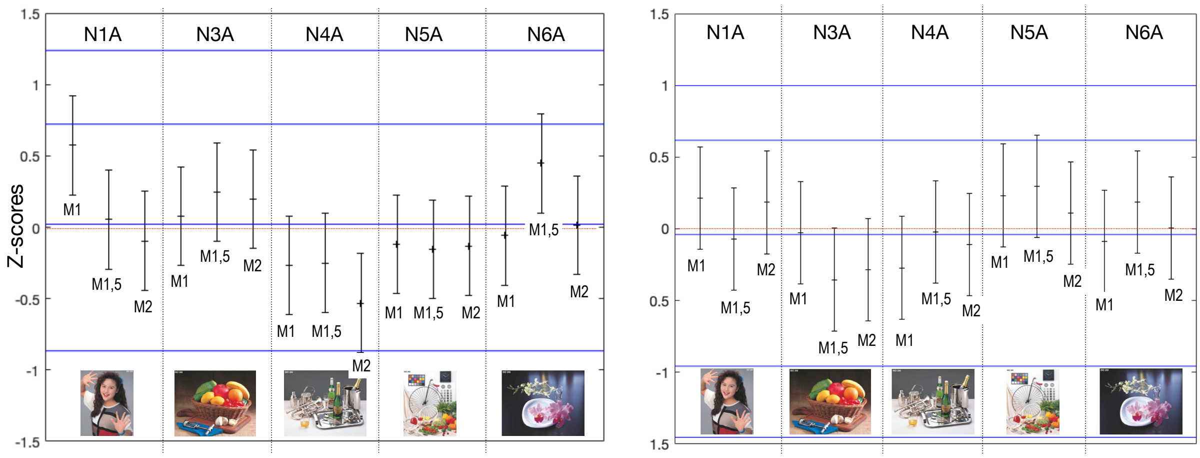

Figure 7: Different image content on 'Textile' substrate under viewing condition 'D50 with-UV (NL)' to the left and under viewing condition 'Daylight (NTNU)' to the right.

3.5. Media-relative adaptation

The results discussed thus far demand consideration of visual adaptation. The fact that the reference displayed on the screen is self-illuminated, while the physical samples are printed on different substrates, suggests that the human visual system is to a degree adapted to the illumination condition and the white point of the medium. This partial adaptation occurs to the perceived media white, regardless of the environment, as evidenced by the varying white points of the substrates.

Since the physical samples were printed with media-relative adjustment, visually, there are differences between the reference on the display and the printed samples. This occurs because the human eye adapts to the white substrate, which fluorescence. As noted by Fairchild [15], the differences between adaptation to display and printed (hard-copy) images have revealed that cognitive mechanisms, which are engaged when viewing familiar objects under known lighting, differ from sensory mechanisms that respond directly to the light's spectral power distribution.

Other studies by Green [16] and High et al.[17] supports the assumption that for on-screen viewing, the observer's state of chromatic adaptation is strongly influenced by the colour of the substrate as well as the viewing illumination and the content of the image itself.

4. Conclusions and future work

Observers scaled the acceptability of hard-copy reproductions relative to a reference soft-proof, using a scale from 'Not perceptible' to 'Unacceptable.' The results show no significant difference between the acceptability of the printed samples under any viewing conditions compare to the reference image on the display, regardless of the amount of UV in the viewing environment and the amount of OBA in the substrate. This outcome is somewhat unexpected, as some of the substrates contain a significant amount of OBA, which one might suspect would result in a noticeably different appearance compare to the reference on the display or an unacceptable judgment by the observer. It implies that adaptation to the media white is the strongest influence on visual acceptability, even in a side-by-side proof-to-print comparison.

Although most participants were experienced in color perception and received thorough instructions for the experimental task, the combination of perceptibility and acceptability thresholds may have introduced some additional bias into the results. Specifically, in printing applications, acceptance is highly dependent on the use case and the individual's role in the production chain (a print buyer generally has higher demands than a print service provider). Thus, acceptability questions should be posed only to experts with professional experience and a specific printing application in mind. Consequently, it may be beneficial to conduct a new psychometric experiment using a category scale that focuses solely on descriptions of perceptions.

To investigate adaptation effects in soft-copy versus hard-copy comparisons, future research could focus on controlled studies assessing how extended viewing times and different lighting conditions (such as daylight and office lighting) influence colour perception. Evaluating colour matching accuracy under various screen calibration settings and paper types including different degree of OBAs, and utilizing psychophysical studies to measure visual fatigue, could provide valuable insights. Employing eye-tracking technology to monitor gaze patterns and developing a psychometric scale to quantify adaptation effects would further enhance understanding. Additionally, examining the impact of surrounding colours and environmental context on colour consistency between digital and printed media would be beneficial.

5. Acknowledgments

The authors extend their gratitude to all participants involved in the psychophysical experiments conducted at NTNU and in the Netherlands. Special thanks are owed to former COSI student Nafia Akter for her invaluable contribution in setting up and conducting the experiment at NTNU.

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