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The impact of the Helmholtz-Kohlrausch effect on the appearance of near-white paper colours

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Abstract

This paper investigates the impact of the Helmholtz-Kohlrausch effect on near-white substrate colours. As the luminance of the test colour (or its simulated reflectance in a soft-proof setup) approaches that of the adapting white point the viewing mode changes from 'surface mode' to 'aperture mode', and the appearance of the test colour becomes self-luminous. However, some substrates with optical brighteners fall close to this threshold between viewing modes, since the OBAs not only increase the perceived reflectance but also increase the H-K effect, where it is very prominent in bluish colours. For graphic arts content shown on a display system, this essentially breaks the soft-proofing paradigm. The practical application of this work relates to cross-media colour reproduction, where the lightness appearance of some substrates is not adequately described by their colorimetric values, and this may impact on choice of proofing strategies.

Introduction

Viewing modes may be thought of as a differentiation between object colours in a lit environment (often referred to as related colours, in the surface reflectance mode, or in the object mode) and colours which are perceived as coming from a lightsource (often referred to as self-luminous colours, or unrelated colours when seen in isolation, or in the aperture mode). In surface mode the perception of an object's relative luminance is one of lightness, whereas for aperture mode the perception of a lightsource's luminance is brightness [1, p.151]. A lightsource is likely to be the brightest part of any viewing environment, and may be thought to 'glow'.

Katayama and Fairchild [2] describe the gradual changes in viewing mode as the luminance of an achromatic stimulus is increased, which is considered to be in the surface mode up to a luminance equal to an adapting white. As the luminance of the stimulus is increased further it may be seen to generate fluorescence, and when increased further still it appears to be self-luminous. Previous work [3] has ascertained an upper limit of the surface mode (above which colours start to appear self-luminous), though the boundary is not so well defined, and there is some discrepancy between the exact boundary reported in [3] and comparable works by other research groups. This may be down to small differences in viewing conditions or experimental setup. For an achromatic colour this lightness limit has L^* of 100 [4] (i.e. that of a perfect diffuser).

Self-luminous displays can be used to simulate surface colours, but only with carefully controlled viewing conditions. The use of soft-proofing in graphic arts is well established, and with careful implementation the displayed image can give an impression of a printed work. This illusion relies upon an adapting white point that may thought of as an achromatic white reference (with an inferred L^* of 100), and this is usually the white point of the display. Relative to this white point, a grey surround with a luminance factor of 0.2 is simulated to be 'behind' the simulated print, and this creates an adapting field that infers the white point even if it is not directly visible in the user interface. Helson refers to this as the 'adaptation reflectance' [5, p.449].

CIE colorimetry underpins the softproofing paradigm, and CIEXYZ and CIELAB are the primary interchange spaces for cross-media colour reproductions. However, both the Munsell system and CIELAB UCS, which are used to describe colours in surface mode viewing, are known to underestimate the lightness appearance of high chroma colours in relation to an achromatic colour of equal luminance reflectance [1, p.111].

The concept that different colours of equal luminance should have the same brightness appearance was used to generate the CIE luminous efficiency ($V\lambda$) function, with the aid of flicker-photometry [6, p.263]. However, this appearance agreement only holds true for this specific viewing condition.

For side-by-side heterochromatic comparisons, where colours have equal luminance, it is seen that perceived brightness may increase as the colours appear more saturated. This is particularly noticeable when comparing high chroma colours to a reference achromatic colour of equal luminance. This phenomenon is referred to as the Helmholtz-Kohlrausch effect [1, p.121].

The inclusion of the H-K effect is problematic for general purpose colour appearance models. The H-K effect was implemented as part of CIECAM97c [7], but excluded from CIECAM97s and subsequent CIE CAMs for related-colours, since the calculations add complexity and are not easily invertible.

Since the brightness of a colour generally increases with its colourfulness, it is clear that the H-K effect makes a significant contribution to the perceived brightness of chromatic light sources (compared to an achromatic source of equal luminance) [8, p.750]. As a result, the H-K effect on brightness appearance is included in the forthcoming CAM20U.

Historically, the Helmholtz-Kohlrausch effect has been modelled separately for surface reflectances (surface viewing mode) and for unrelated light sources (aperture mode). Based upon previous work by Ware and Cowans, the CIE TC1-03 recommended the use of a brightness-lightness conversion factor in 1986 [9]. However, it is made clear that such models are also dependent on viewing conditions and field size (typically 2° or 10°), as well as viewing mode, and are not interchangeable. Some continuity between the viewing modes might be expected around the upper limit of the surface mode, and this was found to be the case by Nayatani [10, p.387] with the proviso that both experimental setups share the same adapting luminance.

Nayatani also advocates two methods of adjustment, namely a method of variable-achromatic-color (VAC) (where the observer adjusts an achromatic test colour to match the brightness of a chromatic reference) and a method of variable-chromatic-color (VCC) (where the observer adjusts a chromatic test colour to match the brightness of an achromatic reference)

[10, p.386]. It is suggested that the different methods can give rise to different estimated magnitudes of the H-K effect. VCC is preferred, since it is more versatile, and can be used to match the brightness of any two colours, whereas VAC is considered to be an easier task for observers to undertake.

Based on a dataset by Sanders and Wyszecki obtained using Munsell reflective samples (2° observer, D65 lightsource, 10° viewing angle), Pirrotta and Fairchild [11] have produced a well-fitted model that modifies the CIE L^* lightness metric to take account of the H-K effect. Their experiment uses a VAC method of adjustment, matching a simulated achromatic reflectance to various Munsell patches in a viewing booth. However, the model is based on colours at Munsell values 3 through to 7, and does not incorporate lighter colours. In fact, the lightness-dependent correction function reaches zero for an L^* of 100, since it is assumed that the H-K effect does not exist for a perfect diffuser. This approach precludes the H-K effect from being predicted for near-white colours.

This present work seeks to identify the H-K effect for near-white colours, including those of commercial print substrates. A more accurate prediction of the perceived lightness of near-white chromatic colours may have application when determining the lightness scaling and the degree of adaptation required to make an appearance match across print reproductions.

Method

A graphic arts display (a wide gamut Eizo CG248-4K) was calibrated and profiled with a D50 white point at a target luminance of 200cd/m^2. Matlab-based software was used to drive a user interface. Target colorimetry was scaled so that the adapting white point appeared to be that of D50 at 120cd/m^2 (together with dim room lighting, in accordance with the P2 viewing condition described in ISO 3664 [12]). The hardware's native white point was thus hidden from view. This allowed some 'headroom' for colours to be generated with luminances higher than the inferred white point of the system, and also with a range of chromaticities around the white point. These would not be achievable with a traditional display setup. This same approach was used previously in [13]. The uniformity and accuracy of the combined system was found to be well within the tolerances for soft-proofing described in ISO 14861 [14].

User interface

The user interface consisted of a full-screen grey surround, with a luminance factor of 0.2 relative to the inferred 120cd/m^2 white point. Reference and test patches were positioned side-by-side with a 2° gap, each patch subtending a viewing angle of 10° (see Fig. 1 for details).

Observers were then asked to adjust the lightness of a series of test patches (either achromatic or of varying chromaticity) until a lightness-match was achieved with the reference patch (which was inversely chromatic or achromatic). The presentation order and left/right patch positions were randomized. Cursor keys were used to increase or decrease lightness, with the additional option of being able to modify the magnitude of the adjustment, before confirming the adjustment with the 'Return' key.

This side-by-side comparison would not be optimal if our aim was to achieve a strict luminance match. However, the configuration is typical of print-to-proof appearance comparisons for different substrates. Similarly, we use D50 colorimetry utilizing the 2° standard observer, in line with a graphic arts approach.

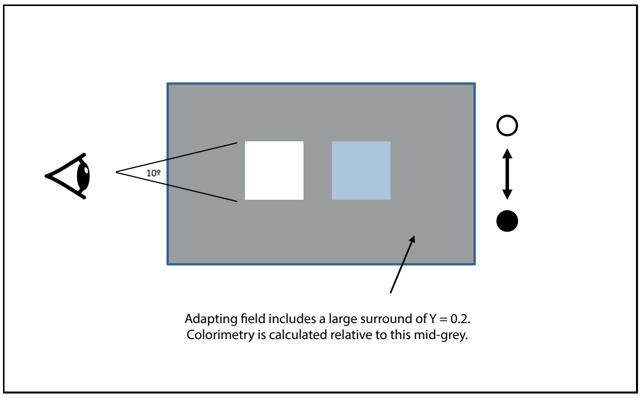


Figure 1. *User interface presented on a 24" Eizo CG248-4K*

A short training session afforded the observers ample adaptation time, and at the end of the session a small subset of patches was rerun to assess intra-observer repeatability.

Directions were given to observers both verbally and in written form, and observer data were captured with an input dialogue box. In accordance with local GDPR requirements, observer data were anonymized at the point of collection.

Method of Variable-Achromatic-Color (VAC)

Reference colours were selected along six hue angles (with h_{ab} of 30°, 90°, 150°, 210°, 270°, and 330°). At each hue angle colours were sampled at three chroma levels (with C^*_{ab} of 10, 20 and 30). These combinations were then mapped to three lightness levels (L^* of 100, 90, and 80). This range of colours may be thought to encompass most commercial print substrates.

For each chromatic reference an achromatic test patch was then adjusted via the keyboard controls to make a lightness appearance match. The starting point of the test patch was always L^*-20 darker than the reference, to avoid adverse adaptation problems or potential display gamut clipping issues. The observer was then free to increase or decrease the CIELAB L^* (in the lightness dimension only), iterating until a lightness appearance match to the reference was obtained.

Where high chroma patches appeared to have a luminance greater than that of a simulated perfect diffuser, and the achromatic patch luminance was then adjusted to match this, this part of the experiment may be thought of as a brightness matching task rather than lightness matching.

Method of Variable-Chromatic-Color (VCC)

For VCC a single achromatic reference was used, a white patch with L^*=100 (essentially the lightness of a simulated perfect diffuser relative to the surround grey, and the adapting white point of the softproofing system). Utilizing the same hue angles and chroma values as before, each test chromatic patch was adjusted until a lightness appearance match with the achromatic reference was obtained.

Observers

Nineteen observers took part (14 male, 5 female) with ages from 22 to 58. All were known to have colour-normal vision.

Results

Initial results showed a greater than expected variability in the data. Observer STRESS was calculated according to [15]. Some individuals were identified as contributing greatly to the uncertainty, and those outliers with either an inter- or intra-observer STRESS that exceeded the 95th percentile upper limit were excluded from the data. Fifteen observers remained.

Variable-Achromatic-Color (VAC) Results

Against a set of reference patches of various hue angles, chroma and lightness levels, an achromatic test patch was adjusted until a lightness appearance match was made (see Fig. 2).

For the VAC method, results show that for reference colour patches with an equal L^* metric lightness there is an increase in equivalent achromatic lightness as their chroma increases. This is consistent with the H-K effect. The effect is quite flat in the yellow region (see Fig. 2b). Previously in [11], the effect has been reported to be strongest in the blue region (hue angle h_{ab} of 270°). The present results show a similarly strong H-K effect from the cyan region through blue and magenta to the red region (see Figs.2d, 2e, 2f, and 2a),though the uncertainty of the results precludes any conclusions to be drawn in finer detail.

The graphed results also show a slight 'dip' in the H-K effect (a lower achromatic lightness equivalent) around a chroma C^*_{ab} of 10. Again, it is within the uncertainty of the results, but a suggestion of this trend appears in results at all hue angles.

In the VAC mode we see a slight increase in observer variability as the chroma of the reference patches is increased (see Fig. 2).

Variable-Chromatic-Color (VCC) Results

Against a single achromatic reference (with an inferred white point L^* of 100), test patches of various hue angles and chroma were adjusted to make a lightness appearance match (see Fig. 3).

The VCC method produces results that are consistent with the underlying trend seen with the VAC method, namely that lightness appearance increases with chroma (and thus a lower metric L^* is required to make an appearance match with the achromatic reference).

The magnitude of the differences in metric L^* between the visually matched reference and test patches are very similar to the VAC above. One exception is the 90° hue angle (yellow) where a far larger compensation was applied to make the visual match in VCC mode (see Figs. 3b and 2b).

As before, observer variability generally increased as the chroma of the test patch was increased. The overall variability for the VCC method was far higher than for VAC, and this concurred with observers' comments in the pilot experiment that the VCC task was far more taxing than the VAC.

For comparison, points are added to Fig. 3 to illustrate a 'gamut of surface colours', sourced from ISO 12640-3:2007 [16, App.B.2], and based on datasets that avoided highly fluorescent samples. A white point of maximum realisable reflectance is not specified in these surface colour data, and therefore the gamut surface shown does not approach any defined white point.

The locus of points which describes a lightness appearance equal to a perfect diffuser sits just above the gamut of surface colours at each hue angle.

Discussion

This experiment covers a range of colours that includes those of most commercially available papers, including proofing papers.

The contribution of the H-K effect when viewing substrates with high OBAs

The addition of optical brightening agents (OBAs) to paper products is a well-known problem for printers, whereby the fluorescing agent absorbs incident light in the near-UV range, and re-emits it within the visible blue range. This is known to create a bluish-white appearance as well as increasing perceived reflectance overall.

For comparison, we take a database of proofing papers known to contain high levels of OBAs [17]. Measurement data are supplied in M1 (UV included) and M0 (tungsten, exact UV content unknown) modes, in accordance with ISO 13655:2009 [18]. The data are compared against the previous VCC results at the 270° hue angle (i.e. a projection against the negative b^* axis). The exact hue angle of each substrate varies, but they are clustered around an h_{ab} of 280°. For these substrates the lightness varies from an L^* of 93.8 (M0) through to 98.0 (M0) or 98.2 (M1, UV inc.), with C^*_{ab} chroma ranging from 2.70 (M0) to 11.70 (M1) (see Fig. 4).

The fluorescence under a light source with standardized UV, when compared to legacy tungsten, has the primary effect of increasing the chroma of these near-white substrate measurements in the blue direction (with a mean shift in b^* of -2.15), whereas the metric increase in L^* lightness is quite modest (a mean increase in L^* of just 0.29).

However, the H-K effect contributes further, with a substrate in the region of b^* -11 seeing an increase in perceived lightness of approximately 2.5% compared to its L^* metric. The plot shows how OBA substrates approach a perceived lightness equal to a perfect diffuser, and in one instance may exceed it. This effect would be even more pronounced with additional UV light.

It can be seen that these substrates are crossing the threshold between surface viewing mode and aperture viewing mode. When this happens the substrate can take on a 'glowing' appearance [6, p.410] that is incongruent with the viewing environment. Similarly, just a small change in the adapting white point in an observer's field of view could change the viewing mode from surface to aperture for these high OBA substrates.

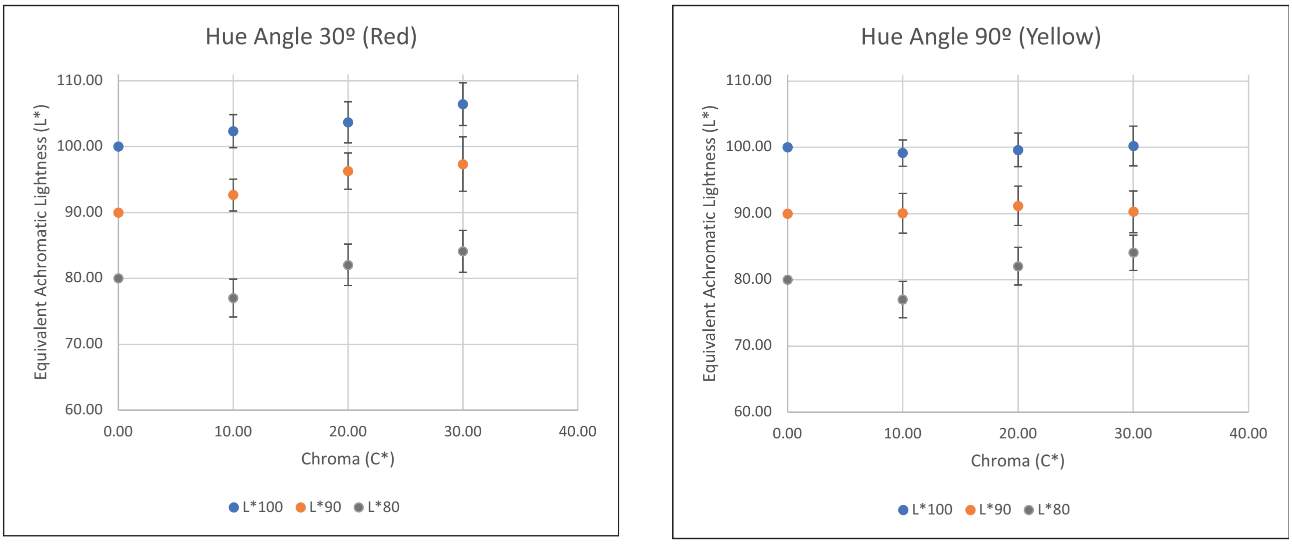
Soft proofing considerations

This experiment was conducted using a specific display setup that allowed the observers to match colours with some 'headroom' in terms of available luminance relative to the adapting white point. From the results we see that some paper colours appear very bright, and these colours often fall outsize the addressable gamut of a display with a fixed white point. It is possible to calibrate a single display's white point to match a known substrate, but this still precludes making a side-by-side comparison with other substrates on that display.

A compromise solution is often to use a chromatic adaptation transform to scale subtrate-relative colorimetry to the display white point. However, we have seen that this would eliminate the perceived lightness increase given by OBAs, and potentially give the simulated reproduction a false appearance.

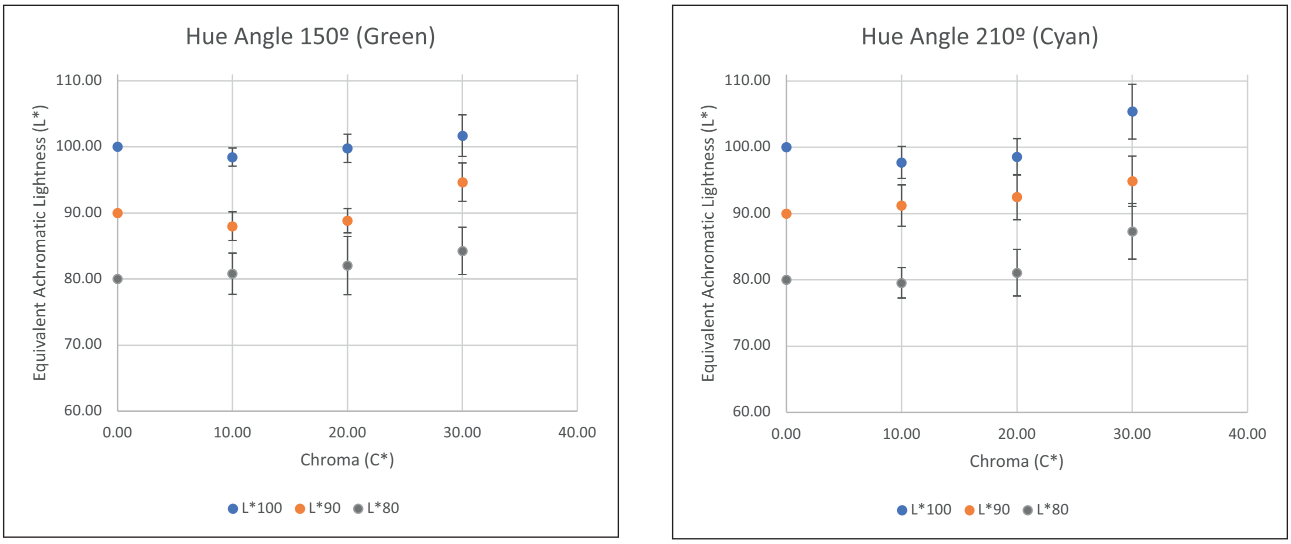
Alternative approaches for deriving lightness matching thresholds

The method of adjustment was chosen for this experiment since it had given good results in previously published work based on reflective samples [11]. However, this approach gives only a single response to each match, whereas the observer's ability to make that match in lightness must depend upon upper and lower thresholds of perceived difference.



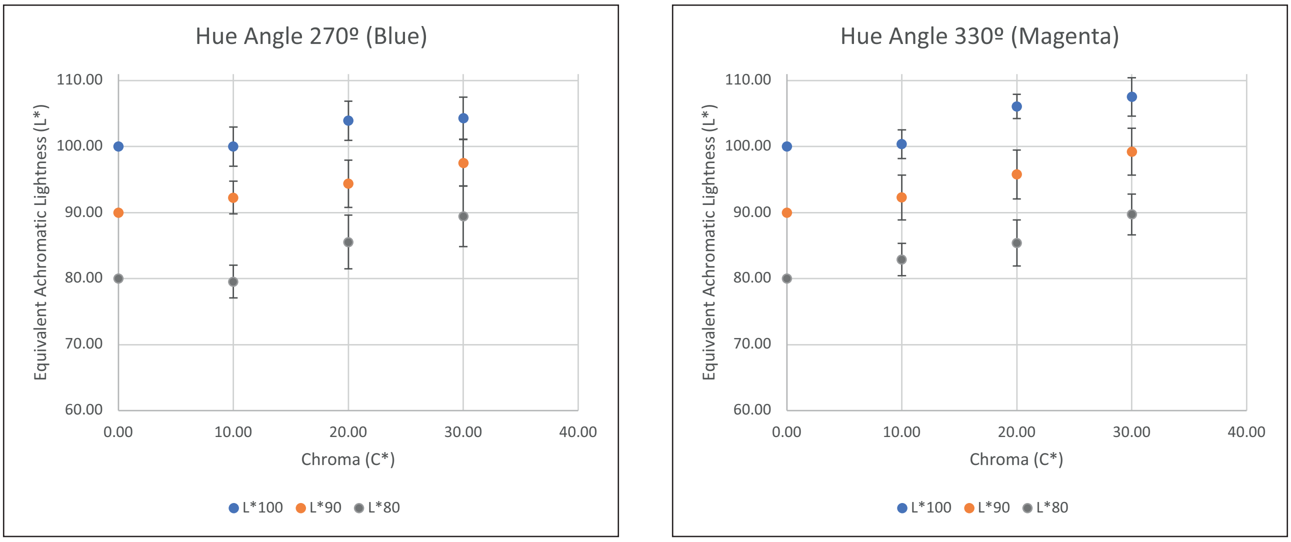
(a) *Chromatic reference patches at hue angle* h_{ab} *of 30°*

(b) *Chromatic reference patches at hue angle* h_{ab} *of 90°*



(c) *Chromatic reference patches at hue angle* h_{ab} *of 150°*

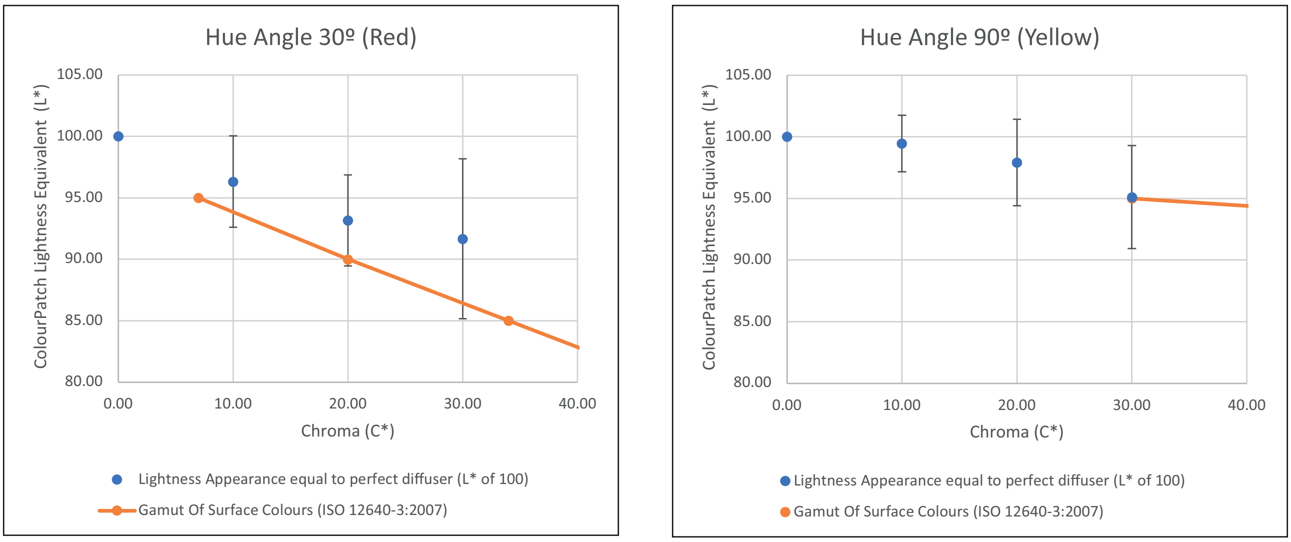
(d) *Chromatic reference patches at hue angle* h_{ab} *of 210°*



(e) *Chromatic reference patches at hue angle* h_{ab} *of 270°*

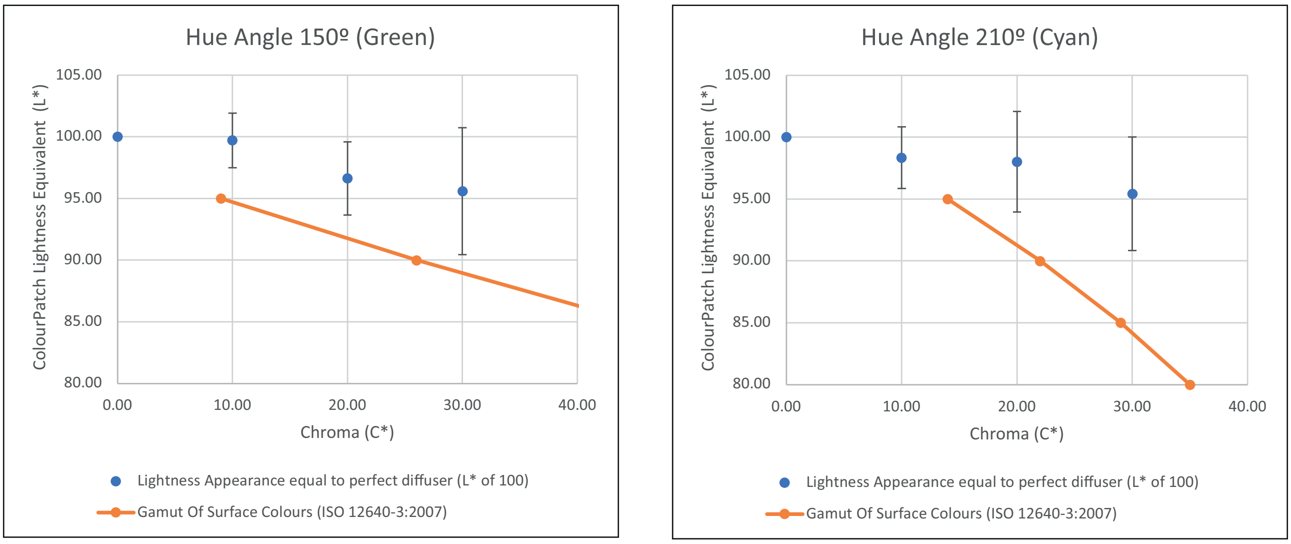
(f) *Chromatic reference patches at hue angle* h_{ab} *of 330°*

Figure 2. *Method of Variable-Achromatic-Color (VAC)*
An achromatic test patch is adjusted in the lightness dimension only, until it has the same lightness appearance as a colour reference patch. The colour reference patches are at six hue angles, and have metric L^* *of 100, 90 and 80. Error bars show confidence interval at the 95%tile.*



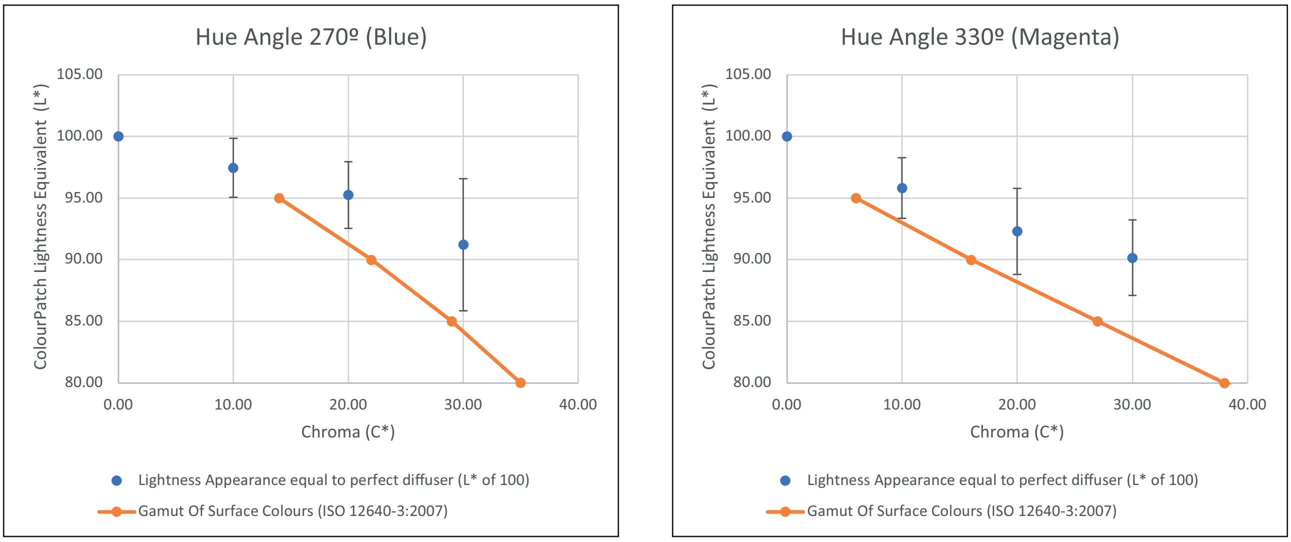
***(a)** Chromatic test patches at hue angle h_{ab} of 30°*

***(b)** Chromatic test patches at hue angle h_{ab} of 90°*



***(c)** Chromatic test patches at hue angle h_{ab} of 150°*

***(d)** Chromatic test patches at hue angle h_{ab} of 210°*



***(e)** Chromatic test patches at hue angle h_{ab} of 270°*

***(f)** Chromatic test patches at hue angle h_{ab} of 330°*

Figure 3. *Method of Variable-Chromatic-Color (VCC)*
Colour test patches at six hue angles and three C^*_{ab} *chroma levels are adjusted in the lightness dimension only, until they have the same lightness appearance as an achromatic reference with a metric* L^* *of 100 (i.e. the user interface's white point). For comparison, the ISO 12640-3 gamut of surface colours is illustrated. Error bars show confidence interval at the 95%tile.*

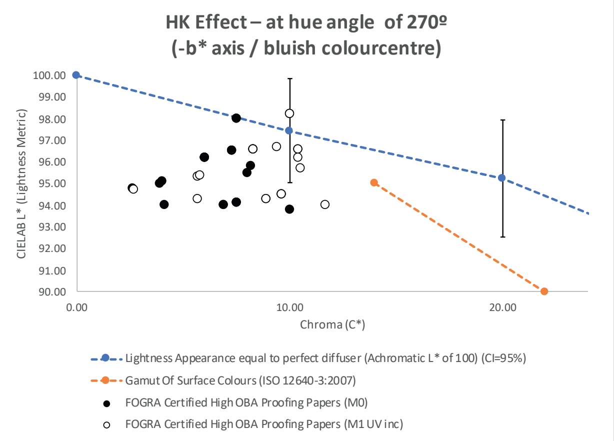


Figure 4. *High OBA Proofing Papers projected onto the b* axis (h_{ab} of 270°)*

A method of limits would have provided these thresholds, and might better explain the levels of variability in some of the results. A method of limits, such as the 'Quest' method, requires a binary decision to be made by the observer. Such an experiment would thus have required two phases of work to facilitate "lighter, or not lighter" and "darker, or not darker" decision making.

Since the present experiment took approximately 45 minutes with only a small patch set, a method of limits would have made this a very time-consuming task for observers.

Similarly useful information could also be derived from an achromatic test vs. achromatic reference lightness matching task, since eliminating the difference in chromaticity would largely remove the potential issue of observer metamerism when using display primaries, and provide a useful baseline for this particular matching method.

Conclusions

The Helmholtz-Kohlrausch effect is present in near-white colours, and has the effect of making blue-white substrates appear even lighter than their metric L^* would indicate.

The H-K effect can be seen to compound the effect of OBAs, which are known to cause a blue-shift in the substrate colour under a UV light source. The bluer the substrate, the greater the H-K effect upon it. The lightening of appearance caused by the H-K effect upon these blue-whites is greater in magnitude than that suggested by the OBA substrates' M1 and M0 L^* metric lightnesses.

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Author Biography

Gregory High is a PhD candidate at the Colour and Visual Computing Laboratory, NTNU, Norway. The topic of his PhD research project is 'A model of consistent colour appearance'.

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