

COLOURIMETRIC OBSERVER CATEGORIES AND THEIR APPLICATIONS IN COLOUR AND VISION SCIENCES

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Abstract

Variability in trichromatic perception leads to observer metamerism, where a colour match for one observer or for a standard leads to a mismatch for another observer with different colour matching functions, specifically when imaging systems with very different spectral characteristics are used for colour rendering.

In a recent doctoral thesis work, the concept of colourimetric observer categories has been introduced where each category represents a distinct colourimetric observer model. An experimental method and a portable prototype instrument have been developed to classify colour-normal observers.

This paper presents an observer dependent colour imaging (ODCI) workflow. This workflow makes it possible to reproduce colours and digital images on an output device according to an observer's category, thus achieving personalised colour reproduction for colour-critical professional applications.

The concept of observer classification has the potential to make a significant impact on various fundamental studies in the domain of colour and vision sciences. Such classification may demonstrate important trends in the visual data that have not been revealed or explored so far.

Keywords: colour perception, observer metamerism, colour vision variability, observer categories

1 Introduction

The most fundamental aspect of applied colourimetry is the trichromacy of our visual system, resulting from three different cone types in the retina. Variability in trichromatic colour perception leads to observer metamerism, in which two stimuli with very different spectral power distribution can produce a colour match for a given observer, but will result in a mismatch for another observer with different colour vision characteristics (i.e. different colour matching functions). This variability among observers with normal colour vision is not typically taken into account in colourimetry, as it is assumed that a single average observer model can reasonably represent the whole population of colour-normal human observers. This model is classically represented either by the CIE 1931 Standard Colourimetric Observer for small fields (1° - 4°), or by the CIE 1964 Supplementary Standard Colourimetric Observer for larger fields. This approximation has worked reasonably well over the past decades in a large majority of industrial colour applications. However, large discrepancies in individual observer colour-matches have occasionally been noticed in some of the more recent digital image applications, in particular those involving wide-gamut displays with peaky primaries, and applications involving Light-Emitting Diode (LED) or Laser based light sources. These discrepancies become most evident when two colour-reproducing systems with very different spectral characteristics are used for colour-matching. The issue of observer metamerism poses a challenge for colour scientists: to find a pragmatic solution that can be effectively implemented in industrial applications.

Toward this goal, the concept of colourimetric observer categories has been introduced in a recently concluded doctoral thesis research [Sarkar, 2011]. Each such category represents a distinct colourimetric observer model. In this work, eight such categories were derived through statistical analyses of existing experimental and physiological datasets of colour-matching functions. An experimental method was developed in order to classify a colour-normal human observer as belonging to one of these categories. This observer classification method was

first implemented using two displays. It was shown that human observers with normal colour vision could be classified into one of these categories based on their colour vision. Subsequently, a compact and inexpensive proof-of-concept prototype, identified as the *Observer Calibrator* in this work, was developed.

The rest of the paper is organised as follows. First, the effect of observer variability in the context of several industrial applications is described. Next, we outline a possible implementation of colourimetric observer categories in a practical colour imaging workflow. Finally, the benefits of adopting the concept of observer classification have been highlighted, both with regard to various industrial applications, and all scientific studies involving psychophysical colour data collection and analysis.

2 Effect of observer variability in industrial applications

The effect of inter-observer variability has often been found to be significant in scientific studies on colour matching, both in the classical and in applied contexts. Observer variability and metamerism can also be a nontrivial issue in industrial applications involving critical colour matching tasks. This is particularly true for those applications that involve various kinds of modern display devices or light-emitting diodes (LEDs).

So far, there have been few attempts to document and report occurrences of observer variability issues encountered in real-world industrial applications. This makes it difficult to realistically assess the frequency and impact of such occurrences in various industrial applications, and the extent and importance of colourimetric failure in such cases. Following subsections highlight some of the applications where observer metamerism is highly relevant.

2.1 Post-production applications

One example is the colour adjustment process (called colour grading) in post-production applications where the raw movie content at the post-shooting stage is modified to achieve the right colour effect. The Colourist has to work with the Director of Photography (DP) to adjust the colours in the original content so as to achieve colour coherence and homogeneity throughout various scenes, while maintaining the artistic expressions originally envisioned by the Film Director and the DP. However, if the Colourist and the DP have different colour vision characteristics and if displays with different spectral characteristics are used, they will perceive colours differently, and the colours that look similar to one will look perceptibly different to the other. Conventional colourimetry will fail to account for this difference.

Further, the film may have to be converted to a version suitable for television or DVD (a process known as digital mastering). This then becomes a cross-media colour reproduction issue, where we are trying to reproduce the colours, as seen on a theatre screen, to equivalent colours on a specific reference display with a certain colour gamut exhibiting restricted colour rendering capacities. Processes like colour grading and digital mastering are colour critical, requiring high-fidelity colour reproduction, often involving displays. Even though film studios have traditionally relied upon reference Cathode Ray Tubes (CRTs), a rapid market adoption of wide-gamut, high-definition displays and projectors and gradual discontinuation of manufacture of CRTs in the recent times require the studios to employ these modern displays for post-production operations.

Very recently, studios have also started offering remote colour grading services, which means multiple devices being used by various professionals at multiple locations for colour grading, a trend that is sure to make the issue of observer variability even more pertinent in the media and entertainment industry.

2.2 Lighting applications involving LEDs

Csuti and Schanda [Csuti, 2008] conducted a colour-matching experiment in a $2^\circ \times 3^\circ$ bipartite field, where one half of the field was illuminated by filtered incandescent lamp, and the other half was illuminated by an additive mixture of RGB LEDs with dominant wavelengths of 626 nm, 525 nm, and 476 nm. Coloured filters were used to generate specific colours on the reference field with the incandescent lamp. Six observers performed colour-matching by changing hue, brightness and saturation of the LED primaries. Colour stimuli were chosen

from various parts of the chromaticity diagram to determine the magnitude of the discrepancy. Differences between visual and instrumental matches increased as one moved in the chromaticity diagram from yellowish white lights toward greenish and bluish lights.

Vidovszky-Németh and Schanda [Vidovszky, 2012] showed that even at equal correlated colour temperature and luminance, brightness perception might depend on the spectral power distribution of the stimulus. Their investigation showed significant inter-observer variability. Interestingly, observers could be clustered into groups for finding brightness equal to, or different from, luminance, depending on the spectral power distribution of the illuminant.

The above two studies provide strong evidence that observer variability can greatly affect lighting applications that involve visual matching with LED light sources. Some of the aspects to be affected by observer variability are LED colour specification, evaluation of colour rendering capabilities and development of colour engineering standards.

2.3 Soft-proofing using modern displays

If colours printed on a hardcopy are matched with the same colours reproduced on various modern displays with narrow-band primaries, it is possible that such colour matching results would vary from observer to observer. Individual observers judging such cross-media colour matches, obtained by using a CIE standard colourimetric observer and colour management principles, may have disagreement about the closeness or even validity of such matches. Following is one such example from a reputed US firm providing printing and related services [Rodriguez, 2012, Hansen, 2013]. This finding dates back to October 2011.

A colour analyst group in the company used two colour-managed displays interchangeably for comparing on-screen images to hard proofs from a high quality printer in a GTI desktop viewer. These displays were calibrated to 5200 K white point using a handheld spectrophotometer. The spectral power distributions (SPD) of display white point on the two displays are shown in Fig. 1. The main difference is in the SPDs of the red primaries of the two displays.

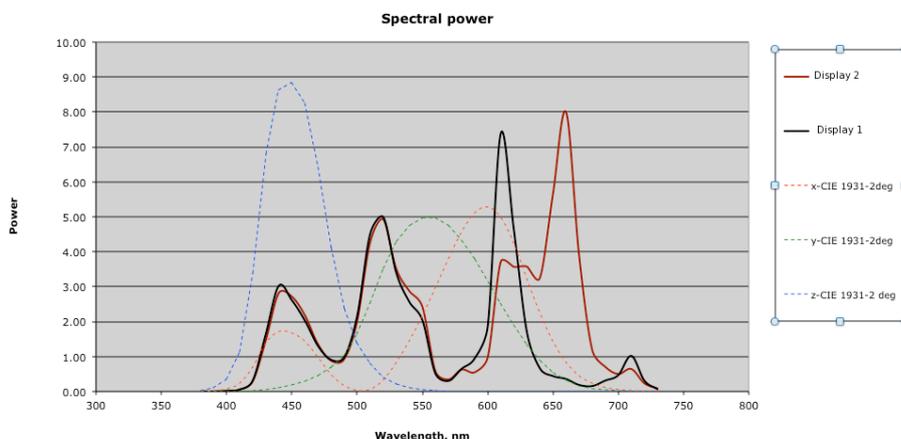


Figure 1 – Spectral power distribution of displays 1 and 2

One of the analysts in the group, it was discovered, saw colours on display 2 as being much warmer than on display 1, especially the neutral colours. Fig. 2 demonstrates how this observer adjusted an on-screen car image to match a hard copy proof of a neutral gray car placed in a 5000 K GTI desktop viewer just next to the display. In particular, he was tending to lower the CIELAB a^* values of neutrals by about eight units during the matching process. For instance, on display 2, he would shift a colour defined as CIELAB (50, 0, 0) to (50, -8, 0), in order to see the display colour match to that on the proof that he was seeing on the desktop viewer [Hansen, 2013]. The figure shows actual adjusted images. The average colour difference between the images is $8 \Delta E_{76}$, with errors ranging between 3 and $13 \Delta E_{76}$ [Rodriguez, 2012]. Most of the difference lies in CIELAB a^* . Such high colour difference

between the two display images was not observed for the rest of the group. This viewer showed no signs of colour blindness and did well on the FM100 hue test. Evidently, the analyst's colour matching functions were significantly different from those of the CIE standard colourimetric observer, which resulted in wide colour differences between the adjusted images.



Figure 2 – On-screen car image adjusted by a colour analyst on displays 1 (left) and 2 (right), to match a hard copy proof of a neutral gray auto placed in a 5000 K GTI desktop viewer placed next to the displays

3 Deriving colourimetric observer categories

A major hypothesis of this work is that human observers with normal colour vision can be classified into a small number of categories based on their colour vision. To be useful, such categories must be appropriately identified and widely agreed upon, and there must be a means to determine which categories should be used under a given circumstance.

Sarkar et al.'s work [Sarkar, 2010] is partly based on the physiologically-based observer model (henceforth described as CIEPO06) proposed by the CIE Technical Committee TC 1-36 [CIE, 2006]. A key assumption behind this work is that the theoretical predictions of the CIEPO06 model and the experimentally obtained visual colour matching data from the 1959 Stiles-Burch study [Stiles, 1959], when combined together, incorporate most of the variability that can be found among the colour normal population. The combined data set used in this study thus included 61 CIEPO06 cone fundamentals corresponding to 20-80 age parameter range, and the cone fundamentals corresponding to 47 Stiles-Burch observers, giving a total of 108 cone fundamentals. A two-step theoretical analysis was performed to find a minimal set of average colour-matching functions that cover all possible variations in this combined dataset.

In the first step, five representative L, M and S cone fundamentals (a total of 125 combinations) were derived through a cluster analysis on the above combined set. A squared Euclidean distance measure (in cone fundamental space) was used in this analysis, and thus was fundamental in nature. The purpose of cluster analysis was to arrange the CMF functions into relatively homogeneous groups based on multivariate observations (108 cone fundamentals as defined above). A K-means method was used to create clusters of CMF objects based on the similarities observed among a set of variables (35 $CMF(\lambda)$ values per CMF).

In the second step, a reduced set of representative observer models was derived from the 125 combinations through an iterative algorithm. For this, several predefined criteria on perceptual colour differences ΔE_{2000} (ΔE_{00}) with respect to actual colour matching functions of the 47 Stiles-Burch observers were used. Colour differences were computed for the 240 Colorchecker DC™ samples simulated under D65 illumination. The goal was to come

up with a minimum set of observer models that would satisfy all predefined colour difference criteria for each Stiles-Burch observer.

4 Experimental method for classifying colour-normal observers

Two setups were developed to test the observer categories principle and as tools to determine which category satisfies best a given colour normal observer. The two setups were defined with the goal to realise colour matches between highly metameric colours in a 10° bipartite field. Colours were presented by pairs to be matched, where the two colours of the pair had significantly different spectra but were perceived as close matches by observers. Observer preferences were analysed after viewing a collection of potential matches corresponding to the predicted categories. The preferred category allowed assigning a category index to the observer. Later this category index could be used to personalise reproduced colours for this individual observer.

The first test setup developed was based on two professional displays with different spectral characteristics. The first one, a Sony BVM-32 CRT, had rather smooth green and blue primaries and a red primary mainly composed of a plurality of spectral peaks. The second display was an HP DreamColor wide gamut LCD display with single and sharper peaks for each primary (see Fig. 3).

The second setup, as described in [Morvan, 2011], was based on two groups of selected LEDs arranged to illuminate uniformly two 10° hemifields in a dedicated instrument (observer calibrator). The RGB LEDs of a first group were selected in spectral regions with low sensitivity variation between categories while for the second hemifield LEDs were chosen to generate higher differences in perception between observer categories (see Fig. 4).

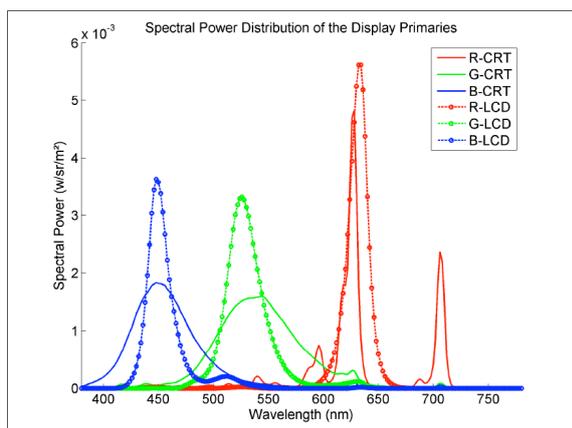


Figure 3 – Spectral power distributions of RGB primaries for the Sony BVM-32 CRT and HP DreamColor wide gamut LCD displays

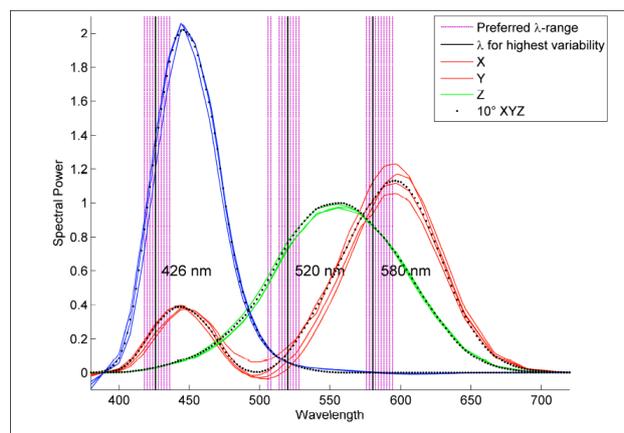


Figure 4 – Wavelength regions of x-, y- and z- functions with high variability among various observer categories

For observer classification, nine matching colours were produced in each half of the 10° bipartite field corresponding to nine observer models (the CIE 10° standard colourimetric observer and the eight reduced set of observer categories). The test software allowed the observer to browse through the nine colour versions with the help of a user control. His or her task was then to follow a multi-step method and classify these nine versions of colour matches into *Superior*, *Average* or *Inferior* categories to perform a relative ranking among them. Based on several such trials (for eight different base colours), the category that most often produces the best match is identified, and is the category assigned to the given observer.

5 Personalised colour reproduction through Observer-Dependent Colour Imaging (ODCI)

As explained in Section 2, observer variability and metamerism can be a nontrivial issue in post-production applications involving critical colour matching tasks, for example the colour grading of the raw movie content at the post-shooting stage. The main goal of colour reproduction in an application such as this is markedly different from that in typical consumer applications. In most consumer applications, colour reproduction focuses on user preferences, but in post-production, the main goal is generally to preserve the artistic intent of the Director of Photography (DP) and the Colourist, irrespective of the ultimate consumer's personal preferences. Doing so for a variety of media, for example, large-screen content (film and/or digital), digital mastered content (television and/or DVD) etc poses a great colour reproduction challenge, even more with wide-gamut displays introduction. At the very least, it is critical that throughout the post-production workflow the colours are represented accurately.

5.1 Colourimetrically accurate imaging workflow

Colour imaging workflow in any practical application can be organised in three steps [Fairchild, 2007]: i) device-dependent representation where colours are specified for a given imaging device only, ii) device-independent representation where colours are specified in terms of colourimetric coordinates such as CIEXYZ or CIELAB, and iii) viewing-condition-independent representation that takes into account the colour appearance of any given scene with specific viewing conditions such as luminance level, surround, chromatic adaptation, etc. and attempt to specify the final image appearance. Even before considering the appearance attributes of the content, the device-independent colourimetric representation, which is quite fundamental from colour science point of view, need to be perfected in order to achieve a colourimetrically accurate imaging workflow.

In this regard, the choice of the colour space is critical. Any colour space specification essentially uses an average or a standard colourimetric observer. Thus, individual variability is an issue that cannot be overlooked, particularly when this variability is significant, either because of the spectral characteristics of the imaging device employed, or because of the observer's colour vision. In fact, many colourists in the entertainment industry usually work on raw colours (device RGB) instead of device-independent colour specifications like CIELAB. Thus the post-production workflow can potentially benefit from an improved, personalised colour space that is perceptually more uniform for a certain individual observer (a colourist or a DP) than what is currently available. This is the ultimate goal of the workflow discussed in the next section.

5.2 The conceptualization of ODCI

In a typical colour image processing pipeline, a significant part of the processing is device independent, irrespective of the devices involved in the input or output side. However, all the processing, whether device dependent or device independent, is based on a single CIE standard colourimetric observer. In his thesis work, Sarkar [Sarkar, 2011] proposed a new workflow to account for observer variability, called *Observer-Dependent Colour Imaging* (ODCI). The concept is illustrated in Fig. 5, applied to some typical colour imaging workflows. However, other embodiments/applications are also possible. Note that the concept of observer dependent colour imaging applies only to a small part of the imaging workflow, mainly at the rendering (output) level, keeping the rest of the chain unaffected.

ODCI workflow will typically be implemented at the output side, for example, for display processing. A display profile-specific transform is currently applied to device independent colour representation, to obtain display colour codes (also described as display channel values or digital counts). The proposed workflow will introduce an additional step (the third, orange block in the figure) where a further transform will be applied based on specific observer setting on the device, and will result in modified display colour codes, customised for a specific observer. This will ensure that the colours perceived by this observer on the display are approximately identical to the perception intended for a CIE standard colourimetric observer, which is the underlying assumption in the whole colour reproduction chain.

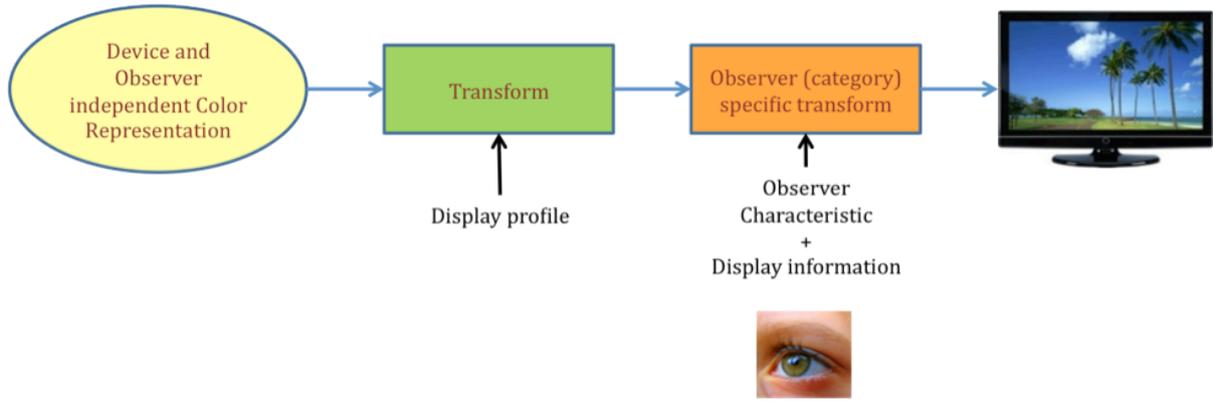


Figure 5 – Observer-dependent colour imaging workflow

5.3 Implementation of ODCI

The observer specific transform described above could be implemented in several ways. In a more device-specific implementation, it could be in the form of observer-specific display Lookup Tables (LUT). Such a LUT would convert digital counts corresponding to CIE standard colourimetric observer-specific colours directly to digital counts corresponding to a given observer category-specific colours. In a more generic, two-step implementation, observer-specific colourimetric transformation can be applied to convert CIE standard colourimetric observer specific values XYZ (henceforth CIEXYZ) to observer category specific XYZ values (henceforth CatXYZ), and then in the next step convert the CatXYZ values to corresponding digital counts through appropriate display LUTs.

Eq. 1 describes the first step. In this equation, $(X_{10} Y_{10} Z_{10})$ are the tristimulus values corresponding to CIE 10° standard colourimetric observer, $(X_{Cat-i} Y_{Cat-i} Z_{Cat-i})$ denote CatXYZ values corresponding to one of the eight observer categories, T_{Cat-i} represents the transformations of CIEXYZ values into the CatXYZ values, and '*' represents a matrix product or a LUT application.

$$\begin{bmatrix} X_{Cat-i} \\ Y_{Cat-i} \\ Z_{Cat-i} \end{bmatrix} = T_{Cat-i} * \begin{bmatrix} X_{10} \\ Y_{10} \\ Z_{10} \end{bmatrix} \quad (1)$$

Two methods were used for computing T_{Cat-i} . The first method used a linear 3x3 transformation, while the second method used a nonlinear spline-based 3D interpolation, described by a three-dimensional lookup table (LUT).

Thus, both methods require that the tristimulus values be computed for a given set of spectral data. For this, estimated spectral power distributions of a large set of stimuli were used in each case. These spectral power distributions were obtained by using the LED primaries in the right half of the bipartite field of the prototype. These colours are characterised by high observer variability. From the spectral power distributions, CIEXYZ and CatXYZ values were computed for each CMF. For each of the two methods, an independent set of eight tristimulus values was used for the verification of the accuracy of the transformation.

Using $(X_{10} Y_{10} Z_{10})$ values from the modeling dataset in Eq. 7-1, $(X_{Cat-i} Y_{Cat-i} Z_{Cat-i})$ values were predicted using a linear (3x3 matrix) or nonlinear transformation (3D-LUT), which were then compared to corresponding tristimulus values computed from the spectral data. The errors between the predicted and actual chromaticity values indicated the accuracy of the transformations. Details for these transformations can be found in Sarkar's thesis [Sarkar, 2011].

Fig. 6 plots the chromaticity coordinates for the eight test stimuli obtained from these CIEXYZ and CatXYZ values. Values obtained directly from the spectral data are plotted as squares while the values obtained through a linear transformation of the CIEXYZ values are shown as triangles. The triangles and the squares are superimposed, confirming 3D interpolation method accurately predicts the CatXYZ values. The empty circles correspond to chromaticities obtained with CIE 10° standard colourimetric observer.

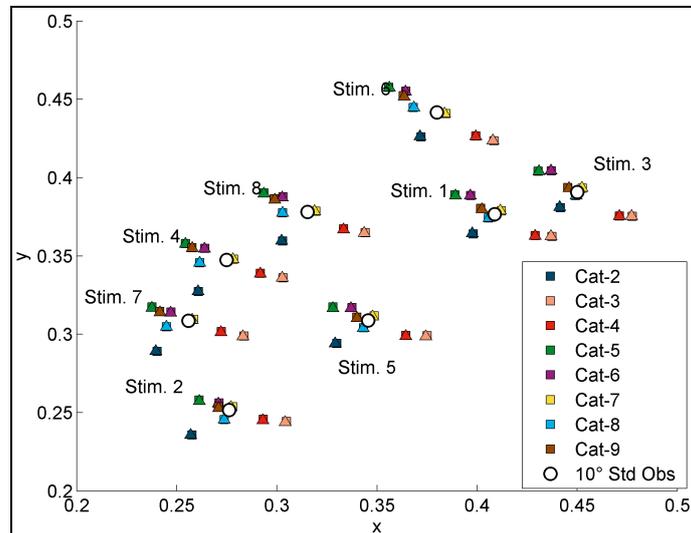


Figure 6 – xy-chromaticities of eight test stimuli corresponding to various observer categories and CIE 10° standard colourimetric observer. Squares: coordinates obtained from spectral data. Triangles: coordinates obtained through 3D interpolation of CIEXYZ values (superimposed on squares due to low prediction errors).

6 Benefits of observer classification in an applied context

As discussed earlier, the issue of observer metamerism has become non-trivial with the advent and widespread adoption of modern wide-gamut consumer displays. Many modern Liquid Crystal Displays (LCDs) are fitted with Light Emitting Diode (LED) backlight (or sometimes, laser primaries) in order to achieve more vivid, more saturated and brighter colours. These displays are particularly susceptible to observer variability [Fairchild, Wyble, 2007, Ramanath, 2009], since their peaky primaries can cause noticeable shift in the chromaticities of perceived colours with relatively minor change in the visual characteristics of the observer. However, the future of televisions and consumer displays lie in these wide-gamut displays. Even monochromatic primaries have been put forward in the UltraHD standardization proposal [ITU, 2020]. Even many latest professional displays are equipped with such narrow-band primaries. The potential advantages of the ODCI workflow should be assessed in this context.

The practical advantage of an ODCI workflow is that it makes it possible to reproduce colours and digital images on an output device according to an observer's category, thus achieving personalised colour reproduction. In an imaging device, e.g. a display, the user can have a control - just like brightness or saturation control typical in today's displays, which will allow him/her to select a specific observer setting. This setting can be selected based on the observer classification test described in the previous chapter, which will make the colours appear to him/her close to what would have appeared to a standard colourimetric observer (i.e. observers with characteristics identical to the CIE standard observer functions). Or, the setting can be based on the default dominant category.

Thus, by selecting an appropriate observer setting for each observer, the variability in the colour perception from one observer to the other can be minimised. This could significantly

reduce the uncertainty in colour critical tasks introduced by observer variability. An example could be colour correction by a colourist during post-production, where any potential disagreement between colourists or between a colourist and the Director of Photography can be minimised by selecting (through user control) an appropriate set of CMFs for each person.

The concept can be applied to any application of Digital Image Processing/Digital Video Processing. It could, in principle, be applied to any industrial application involving colour management and reproduction.

Specific to the application contexts relevant for content processing, ODCI has potential to help develop technologies for observer-dependent colour correction method in post-production workflow. More generally, graphics arts and the use of creative computer software can benefit from the workflow proposed here. It is also applicable to high quality colour reproduction for TV/PC end users as observer dependent calibration can easily be implemented in the form of a Look-Up Table transform in personal computers, set-top boxes or gateways.

In soft-proofing applications employing modern displays, where a colour analyst views and compares colours between hardcopy outputs and reproduction on one or possibly multiple displays with narrow-band primaries, the ODCI workflow can help achieve more accurate colour-matching results.

The ODCI workflow is likely to be most useful for professional and high-end consumer display applications. Since the main goal of such a workflow is personalised, high-fidelity colour reproduction, it may not be as useful when several users with varied colour vision are simultaneously consuming the content.

7 Relevance of observer classification in scientific studies

Observer classification can also prove to be very useful in scientific studies that include visual experiments involving colour stimuli. Such classification may demonstrate important trends in the visual data that have not been revealed or explored so far. For example, it might be possible to better explain outliers in observer data in a psychophysical experiment, or to integrate them back in result, as their deviate scores may be explained by color categorisation. With regard to colour science, there are many unanswered questions that need to be explored.

For example, what are the effects of applying observer categories on suprathreshold colour difference judgment data? Kuehni [Kuehni, 2009] studied the variability of small suprathreshold colour difference perception using colour difference scaling data from two well-controlled experiments, one involving judgments if the differences represented by chromatic sample pairs are perceptually smaller or larger than that between an achromatic reference pair, and the other involving assessment of the magnitude of the sample pair differences using a 9-grade gray scale. The analysis revealed a large inter-observer variability in the estimated magnitude of chromatic differences compared with achromatic reference pairs, with an average ratio between largest and smallest colour difference estimate of over 3:1, and ratios for individual observers and sample pairs ranging up to 28:1. Kuehni observed that the mean observer data depended to a significant degree on the composition of the observer panel, and concluded that the colour difference formulas fitted to mean data could predict perceived colour differences accurately only for one third of colour-normal observers.

A correlation analysis [Fetudina, 2011] was performed on observer classification data from a collaborative experiment, and suprathreshold colour difference judgments obtained from an independent experiment involving the same set of observers. Some interesting correlation was observed between the observer categories and perceived colour differences. Firstly, colour difference thresholds for categories that were very different from the CIE standard colourimetric observer, as indicated by the observer classification results, had large differences from the global average thresholds. Secondly, average thresholds for observers belonging to dominant categories were generally very close to the global average thresholds. The consistency between observer categories and colour difference data make it plausible that colourimetric observer categories, derived from classical colour matching data, can help

in a more accurate prediction of average suprathreshold colour difference perception for a given observer population.

Can the application of observer categories have an influence on the perceptual uniformity of a colour space? Thornton [Thornton, 1998] has discussed how the chromaticities of strongly metameric lights that are deemed a visual match by real observers can be spread widely across the chromaticity diagram or the CIELAB colour space, amounting up to 40-50 ΔE^*_{ab} . Thornton observes that this is due to the poor performance of CIE standard colourimetric observers in the presence of strong metamerism.

Viewing this issue from a different perspective, we can hypothesise that if we are able to identify a more homogeneous group of observers with the help of observer classification technique, we might be able to reduce such discrepancies in chromaticities of perceived colours of strongly metameric stimuli. Going a step further, we can apply a transformation function (see section 5.3) to the visual data belonging to a given observer category, and convert them to generic visual data, belonging to say a CIE standard colourimetric observer. As a result of such transformation, better perceptual uniformity of colour spaces can be achieved even in the presence of strong metamerism.

However, this is not to suggest that we can explain all of the variability in suprathreshold colour difference data with the help of colour matching data. Colour difference judgment involves additional physiological processes that do not play a role in a well-designed colour matching experiment. For example, in his analysis of colour-matching error data and colour difference data in the L, M, S cone space, Kuehni [Kuehni, 2001] observed a “sharpening or weakening of discrimination as a function of surround, resulting in relatively larger increments required the further the chromaticities of the compared fields differ from that of the surround”. He thus concluded that the shape of uniform colour space depends on the size of the colour differences and on the surround.

8 Conclusion and future work

The main motivation behind the work described in this paper was to find a practical solution to the problem of observer metamerism in industrial applications. The most important contribution of this work has been to prove that human observers with normal colour vision can be classified into a small number of categories based on their colour vision. For this, a set of eight colourimetric observer categories was proposed for use in colourimetry, along with an observer classification method, and a proof-of-concept prototype: the Observer Calibrator. In this regard, it must be emphasised that there is no unique way to derive these observer categories. It is expected that future research on the topic would yield more optimised and a minimal set of unique categories.

While the above aspects have been briefly reviewed in this paper, the main focus here was on the applied aspects of the work. The paper started by identifying some of the industrial applications where observer metamerism can be expected to be significant, outlined a possible implementation of colourimetric observer categories in a practical colour imaging workflow, and finally, highlighted the benefits of adopting the concept of observer classification in industrial applications and scientific studies.

With regard to industrial applications, observer classification is not the only possible way to address observer metamerism in industrial applications. A strong candidate is multispectral imaging, which has been proposed for the motion picture applications [Long, 2012], for display design in the form of a field-sequential colour display with primary spectra synthesised by a temporally-averaged, modulated array of light sources [Bergquist, 2008], or for high-fidelity video and still-image communication (Natural Vision project) [Yamaguchi, 2006] among others. Indeed, under certain circumstances observer classification may not be an ideal solution, in particular for applications necessitating simultaneous content viewing by multiple observers.

The contributions of this work have scope well beyond a handful of professional colour-critical applications. Findings of this work can have significant implications for fundamental studies in the domain of colour and vision sciences. The concept of observer classification opens up

new possibilities and raises interesting questions that must be pursued by the scientists and researchers. Preliminary results obtained during the thesis research should encourage them to embark on such a quest with a sense of urgency.

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