Observer metamerism and colorimetric additivity failures in soft-proofing

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Abstract

Eleven observers made colour matches between LCD and CRT monitors and paint samples in viewing conditions similar to those of soft-proofing. The matches were used to evaluate the practical significance of observer metamerism and of failures of colorimetric additivity in cross-media colour matching.

The individual variations in matches are of magnitudes that are expected to have practical consequences in graphic arts applications; they can not be explained by observer metamerism and thus can not be modelled by the Standard Deviate Observer. At the other hand, these variations are modelled well by the CIEDE2000 colour difference formula.

Failures of colorimetric additivity lead to systematic disagreements in cross-media matches made by individual observers and predicted by the CIE 1964 Standard Colorimetric Observer. The discrepancies are consistent with all the reports on the subject, but have never been confirmed to exist in practical colorimetry. A chromatic adaptation modelling framework can be used to compensate for the failures in practical applications.

We conclude that additivity failure is a significant contributor to the uncertainty of colour matching, and needs to be accounted for in industrial colour management systems. The practical implications of individual variability which is not the result of observer metamerism remains unclear.

Introduction

The CIE Standard Colorimetric Observer [1] represents the average Colour Matching Functions (CMFs) of observers with normal colour vision. Values calculated with the Standard Observer are subject to uncertainty of two kinds: physical and psychophysical. The physical uncertainty results from random fluctuations of the measurement instruments and of the measurand, and methods of its evaluation are established [2, 3]. The sources of psychophysical uncertainty can be broadly broken down into two categories:

1. Individual variations in CMFs and their consequence – observer metamerism
2. Failure of the principles underlying the mathematical construct of CIE colorimetry, notably the failure of colorimetric additivity.

The practical consequence of the psychophysical uncertainty is that a pair of stimuli which is a metameric match to the Standard Observer can mismatch to a real observer. Both sources of uncertainty are long known but so far largely neglected in practical colorimetry. Their effect on industrial tasks is unknown, or at best known only from anecdotal evidence. The purpose of this study was to fill this gap between theoretical and practical knowledge at least for one practical application – soft-proofing. We aimed to simulate the task of matching the display colour to object colour, and to answer the following questions:

1. Are individual variations in CMFs statistically significant and do they have practical consequences?
2. Do additivity failures have practical consequences?
3. If the answer is positive for either question then - how can these consequences be modeled and accounted for in practical colorimetry?

Background

Observer metamerism

Observer metamerism is the direct consequence of the individual variations in CMFs, and results when a pair of stimuli with different spectral power distribution (SPD) matches to one observer and mismatches to another. Wright published one of the first evaluations of individual differences in CMFs [4]. 36 observers made narrow-band matches of white light, and the match chromaticities were plotted in the same diagram. The plot shows wide spread of chromaticities; this is the first example of use of the method utilised extensively afterwards, whereby matches made by different observers are plotted in the diagram of some reference observer. For every data point, the distance from the mean match is representative of the colour difference that the reference observer would see when presented with the individual observer's match.

Later, Stiles and Burch study [5] generated the largest and the highest quality colour-matching data set so far, which was used in a number of studies on variability of CMFs [6-9]. Besides the well known [10] (pp. 347) sources of variability such as individual variations in lens and macular pigment density, additional factors modifying colour matching are variation in effective optical density of the cones and shifts in peak cone responsivity. The latter variation is known to have origin in the polymorphism of the red and, possibly, the green photopigments [11-13].

While literature on sources and magnitudes of individual variations in bipartite field narrow-band colour matches is rich, our knowledge of implications of these variations on matching "real-world" metamers is surprisingly limited. Kaiser and Hemmendinger [14] report results of observations made by 59 observers, 17 to 64 years old, using the Davidson & Hemmendinger Color Rule, under two illuminants. There is a clear linear relation between matches and age. Billmeyer and Saltzman

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[15] reported results of a similar study with 72 students as observers, mostly of relatively young age.

In cross-media colour matching the available knowledge is rather limited as well. Pobboravsky [16] did a limited-scale psychophysical experiment, and computationally evaluated the spread of matches that would be expected from a published sub-set of CMFs of 20 observers [10]. His conclusion was that *"color vision differences between normal observers appear to pose no problem for the comparison of soft and hard proofs."* Matches made by anomalous trichromats were "*clearly unacceptable*" by the normals, and *vice versa*.

Rich and Jalijali [17] published a report of an experiment very similar in principle to Pobboravsky's [16], but with rather different conclusions. Observers matched a series of neutral surface colour samples by adjusting the colour of a CRT display. The chromaticity plot of the results shows a large spread, but no numerical data is reported.

Alfvin and Fairchild carried out a "hybrid" of classical and cross-media colour matching. Observers matched CRT colour to surface samples arranged in a 2.9° bipartite field, whereby the observers did not know the origin of the stimuli. The mean colour difference from mean (MCDM) for inter-observer variation was 2.67 CIELAB (2°/D50) units. The question of relevance of the experimental conditions to industrial practice was not discussed.

Rich and Jalijali [17] conclude their paper with *"…a plea for a commercially viable special index of metamerism for change in observer…"*. To the best of our knowledge, no definitions or description of requirements for such index exist in the literature. For cross-media colour matching, there is no quantitative data derived in industrially-relevant conditions that indicates that such an index is even necessary. As Allen [18] notes: *"Before we try to fix an index for metamerism, we must clearly define just what it is we are trying to index."* This notion is still relevant today.

Failures of colorimetric additivity

The law of colorimetric additivity and its quantitative formulation - the Trichromatic Generalisation [10] (p. 118) - are the basis of the mathematical construct of colorimetry. It allows handling of quantities of colour stimuli with accordance with standard rules of algebra. The validity of colorimetric operations is strictly dependent on the validity of additivity law.

Reports of failures of additivity have long history. The first such report appears to be published by Blottiau [19] (reviewed in [20]). Large deviations from additivity were observed in blue tristimulus values. This is the first time when a possible link was shown between additivity failures and the blue cone mechanism.

Colorimetric additivity can be tested by comparing tristimulus values measured directly by visual colour matching with ones calculated using the same observer's colour matching functions. Trezona [21] performed this test, and found deviations from additivity: the match made directly is significantly bluer than the one predicted by the calculation. This feature can be found in almost all the additivity experiments ever since. Stiles [22] did experiment similar to Trezona's [21] and found failures of additivity in one third of his 47 observers, affecting mostly blue tristimulus values. Lozano and Palmer [23] did a similar test but with twenty broadband stimuli; the results have shown additivity failure of the same character. Zaidi [24] attempted to identify possible causes for the failures; he concludes that they can result from change in shape of responsivity of the blue cone mechanism driven by an unknown adaptation mechanism and/or postreceptoral processing.

In colorimetry the existence of additivity failures was largely ignored, and their consequences were not studied. Thornton [25] was the first to report a practical consequence: the procedure of transformation of tristimulus space fails; this finding was confirmed by the present authors [26, 27]. The effect of additivity failures on other colorimetric operations remains unknown.

The experiment

Experimental setup

In a cross-media asymmetric [10] (p. 281) colour matching experiment, observers match the colour of paint samples by manipulating LCD and CRT monitors, arranged as shown in Figure 1.

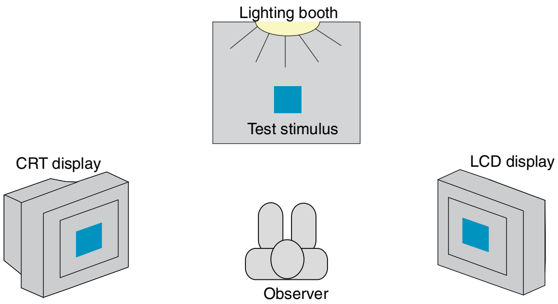


Figure 1. Experimental setup

The CRT and LCD displays were LaCIE BlueIV and LaCIE 321, equipped with hoods to minimise stray light reflections. The viewing booth was VeriVide DTP-60, with the fluorescent light source having CCT of approximately 6000K; the inner surface was covered with black velvet, and the luminance monitored by a luminance meter affixed to the booth floor. Observers wore black shirts during the experiment in order to avoid reflections of their clothing from the monitor surface. No light sources operated in the laboratory apart from the two displays and the viewing booth. Spatial and temporal properties of both monitors and of the viewing booth were evaluated prior to the experiment; all were found to be satisfactory for our purposes.

Any colour match between the monitors and the paint sample, and between the two monitors, is metameric: the SPDs of the lights reflected from the sample and emitted by the monitors are different. The SPD of the grey paint sample and lights emitted by the two displays all having same CIE 1964 XYZ values are shown in Figure 2.

Ten paint samples were used as test stimuli: two achromatic (white and medium grey) and eight chromatic, spanning the CIELAB a*b* plane in hue angle steps of approximately 45°.

All stimuli subtended 6° at the experimental viewing distance (approximately 80 cm), and were surrounded by a grey background of approximately 60°×40°.

The maximum luminance of both monitors was 120 cd/m^2. The luminance of the white paint sample was 110 cd/m^2.

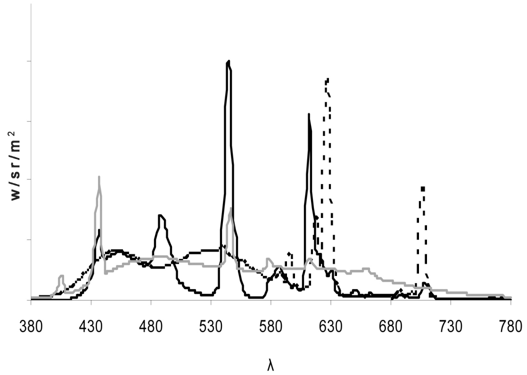


***Figure 2**. Relative spectral power distribution functions of grey sample displayed on the LCD and CRT matching in colour the grey paint sample in the viewing booth for the CIE 1964 Standard Observer. Grey line: paint sample; black solid line: LCD display; black dashed line: CRT display*

Experimental procedure

On each of the monitors, observers accomplished the colour matching task in two stages:

1. *Adjustment of the background.* At the beginning of the first session, observers adjust, starting from black, the colour of the background on both monitors to match the grey background in the viewing booth. At the beginning of each of the following sessions observers verify that the grey background on the monitors still matches the one on the booth, and do appropriate adjustments if it does not.
2. *Establishing the colour match.* Observers alter the colour of central patch on each of the monitors in turn to match the colour of each of the ten paint samples in turn.

In the first stage, observers establish the viewing conditions on both monitors to be identical to those in the viewing booth: i.e. the colour of the background on the monitors matches that in the booth for the particular observer, but not necessarily for the Standard Observer. In the second stage, the observers establish a colour match between both monitors and the paint sample.

The first test stimulus in all sessions was white; during this match the observers adjusted both the test stimulus and the grey background. The adjusted background was used to display the rest of the test colours, which were randomised in every session.

The initial position from which the observers started to adjust the colour was always black. Observers controlled the monitors' colour by rotating the mouse wheel, in one of two modes:

- CIELAB L*, C^*_{ab} and h^*_{ab} (used for chromatic stimuli)
- CIELAB L*, a* and b* (used for achromatic stimuli)

The duration of the adjustment was not limited; the average session lasted about one hour. Radiometric measurements of the matches made on both monitors were taken upon completion of the observation sessions on the same day. The paint samples in the viewing booth were monitored on daily basis – also by radiometric measurements. Hence, all the results reported here are based on direct measurements of the stimuli, and are independent of the calibration state of the monitors. The radiometric data were used to calculate CIE 1964 XYZ tristimulus values.

The CIE 1964 XYZ tristimulus values of the booth illuminant were calculated from radiometric measurement of a white ceramic tile of known reflectance, and were used as the reference white in the CIELAB calculations.

Eleven observers took part in the experiment, eight males and three females, aged 32 years on average, all colour science postgraduate students, experienced in making colour judgements and in performing psychophysical tasks. All were screened for colour vision deficiencies by Ishihara pseudoisochromatic plates, Farnsworth- Munsell 100 Hue Test, and D&H Colour Rule.

Each observer performed five repetitions of each of 10 matches, all on different days. In total, 1100 matches were made.

Results

Additivity failure

The geometric configuration of the stimuli on the displays and in the viewing booth was similar. The colour of the background grey on the monitors was adjusted individually by each observer to match the background in the booth. Thus, the viewing conditions for the stimuli on the display and in the booth were nearly identical. In such a setup, it is reasonable to expect that, while each observer will be different from the standard, the mean match of eleven observers would be very similar to the CIE 1964 Observer prediction. This is not so: the mean adjustments of all colours except Yellow and Brown are shifted towards blue-purple (Figure 3). In other words, the observers used more blue light to match the paint sample in computer displays than the CIE standard observer predicts.

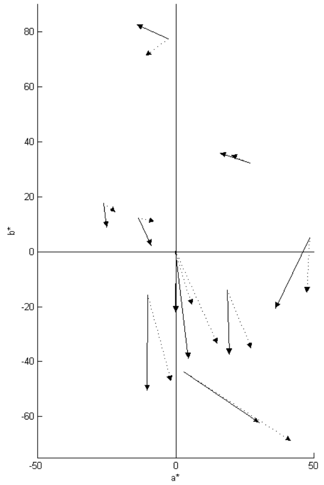


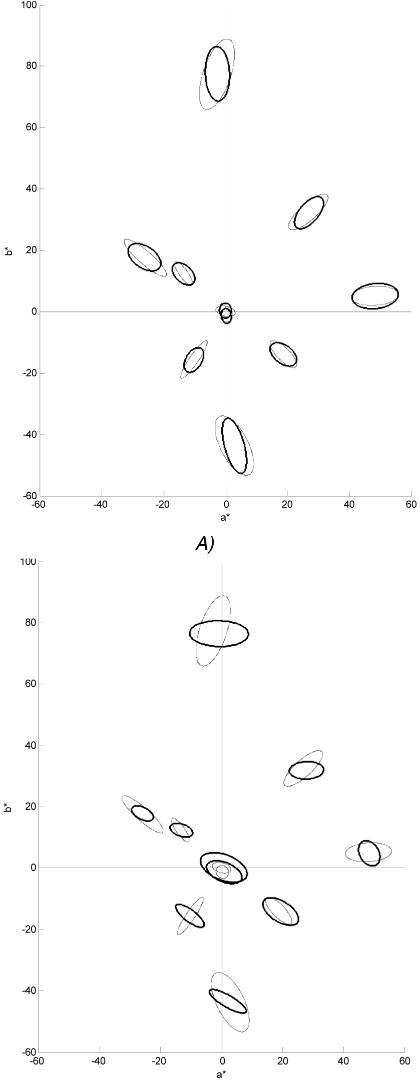
***Figure 3**. Systematic "blue" shifts in display colours visually matching paint samples, illustrated as vectors with the origin at the coordinate of the paint sample, and head at the coordinate of the mean match made by observers on LCD display (solid line) and CRT display (dotted line). a*b* plane diagram, vectors are scaled up ×10*

The mean CIEDE2000 a*b* difference between the paint sample and mean observers' match for colours where the discrepancies were significant (white, grey, magenta, purple, blue, cyan) was 1.95 CIEDE2000 units, with the maximum of 3.75 in white. The L* difference is ignored in this calculation because the blue cone mechanism, which is believed to be responsible for the discrepancies, does not contribute to perception of lightness.

The behaviour differs somewhat for the two monitors. In Figure 3A, vectors resulted from the discrepancies in CRT colours appear to be rotated anti-clockwise relative to ones of the LCD.

Individual variability of colour matching

The mean inter-observer variability of matches was 3.2 and 2.9 CIEDE2000 units for LCD and CRT displays respectively. There was no significant difference in either intra- or inter-observer variability between the two displays. The inter-observer variability is illustrated graphically in form of 95% confidence ellipses in Figure 4, and is discussed below.



A)

B)

***Figure 4**. 95% confidence ellipses of observer's adjustments plotted in CIELAB a*b* diagram A)CRT display (thin line) superimposed with 2 ΔE_{00} contour ellipses (thick line); B)CRT display (thin line) with ellipses created for Stiles and Burch [5] 47 observers (thick line) (scaled up ×10). See text for details*

Discussion

Additivity failures

The discrepancies between the Standard Observer and the real observers take the form of a shift towards blue; they are most significant in the lower half of a*b* diagram and in neutrals. Moreover, these discrepancies are stronger for white than for grey. In the green-yellow-orange region the discrepancies are minimal or non-existent.

Cone excitation caused by members of a metameric pair is identical, hence the adaptation caused by both stimuli is identical and the match is not upset; this is the "law of persistence of colour match". If each of the metameric stimuli causes different adaptation the match is upset, and additivity does not hold. Failures of colorimetric additivity are often said to be caused by adaptation [24, 28, 29]. We are not aware of any description of mechanisms underlying this effect, although some speculations involving an unknown photopigment layer in the retina [7] and the relationship between blue cone responsivity and red-green cone excitation [24] have been proposed. Because of the similarity of our results to previous descriptions of additivity failures caused by adaptation, we attribute our discrepancies to the same phenomenon

Due to this link between adaptation and additivity failure it was of interest to try to model the discrepancies using an available model of chromatic adaptation – CAT02, part of the CIECAM02 colour appearance model [30]. The test white point was given by the viewing booth illuminant. The display, however, did not have any pre-set white point: all the adjustments began from black, including the adjustment of the background. Therefore we tried to empirically assign different values to the reference white point, until the CIELAB colour difference between the CAT prediction and the mean observers' match was minimised. This was done for each stimulus separately. No single adapting illuminant could explain the observed discrepancies, while the average illuminant values had chromaticities similar to CIE D65.

The effect reported herein is consistent with all previous reports of additivity failures in colour matching, which can be summarized as follows: *when colour matching functions measured with narrow-band lights are applied to the prediction of metameric matches between narrow-band and broadband stimuli, the calculated "blue" tristimulus values of the mixture of narrow-band stimuli are smaller than the ones set by visual colour matching of the broad-band stimulus*. The light emitted by the LCD and CRT displays is in part narrowband due to the red primaries in CRT and red and green primaries in LCD. Therefore, if this assertion is correct, they are affected by this phenomenon, as is any colour reproduction device which generates narrow-band lights.

The discrepancies for LCD and CRT are nearly identical in magnitude. The only difference is a small but very consistent anti-clockwise rotation of the shift vector for the CRT display relative to the LCD (Figure 3). The primary lights of the two display technologies differ in red and green: in red there is the far-red peak around 700 nm in CRTs which does not exist in LCDs, and in green the LCD primary is significantly more narrow-band. These are the only major differences between the lights emitted by the two displays; however, just how this difference results in the observed behaviour remains unclear.

To the best of our knowledge, the present report is the first to describe, characterise and quantify the failure of colorimetric additivity in conditions relevant to practical colorimetry. However, the effect we describe is long known by the practitioners in the field, and significant anecdotal evidence exists. Hunt in "The Reproduction of Colour" [31] (p. 390) states that displays adjusted to have a white point of CCT below 3000K look "*intolerably yellow*". Rich notes [32] *"…the monitor could be made to provide good visual simulations of the prints … but the tristimulus values … were very far from being equal"*. In colour management it is commonly advised to calibrate the displays to a higher temperature white point than the viewing booth to achieve better visual match.

The relationship between additivity failures and adaptation suggests that this problem can be treated in colour management by an appropriately designed chromatic adaptation transform, which accounts for a possible nonlinear change in the shape of the responsivity of the blue cone mechanism.

Individual variability of colour matching

The ultimate aim of an investigation into observer metamerism is a model which would allow prediction of the uncertainty of colour matching. The CIE Standard Deviate Observer (SDO) was an attempt to achieve this aim; however it was not accepted by industry and was shown to significantly underestimate the extent of observer metamerism [33-35]. The CIE SDO is based on a concept developed by Allen [18]. The applicability of Allen's model for conditions different from quasi-symmetric colour matching with narrow-band lights was never shown. We attempted to test this applicability analytically.

Colour matching can be mathematically modelled if the SPD of the primary lights and the colour matching functions of the observer are known [16]. When done for a set of CMFs of a group of observers, the spread of matches thus constructed corresponds to the magnitude of observer metamerism within the group of observers for a particular "display-surface colour" metameric pair. We constructed such a set for the 47[†] CMFs of the individual observers in Stiles and Burch [5] dataset.[‡] The resulting set of SPDs was converted into CIELAB coordinates and used to construct 95% confidence ellipses in the a*b* plane.

The mean variation within the Stiles and Burch observers is 0.51 and 0.55 CIEDE2000 units (MCDM), with a maximum of 1.2 in white. This is consistent with the result of similar calculations made by Pobboravsky [16]. This suggests that observer metamerism is very unlikely to lead to visually-significant differences in cross-media matches made by different colour-normal observers – as also confirmed by Pobboravsky. However, the mean variability of matches in our experiment was significantly higher – about 3 CIEDE2000 units.

The graphical illustration of the results in Figure 4 suggests an explanation. In plot B), ellipses for eleven observers' mean matches are plotted with the ellipses of the 47 Stiles and Burch observers (scaled by a factor of 10). With few exceptions, the discrepancies in relative size and orientation of the two sets of ellipses are apparent. In the same figure, plot A) shows the same 95% ellipses for our eleven observer's matches, this time superimposed with 2 units of Delta E 2000 (ΔE_{00}, [36] contours; i.e. every point on the ellipse lies at the distance of 2 units of ΔE_{00} from the centre. This time, the similarity in sizes and orientation is remarkable. The plots show data for the CRT display; the LCD results are very similar.

We do not have reason to believe that the 47 observers of Stiles and Burch are not representative of human colour-normal population, or that their colour matching data is unreliable. If asymmetric cross-media colour matching is governed strictly by the rules of metameric matching then it should be possible to model it from the Stiles and Burch dataset. From our results reported herein, we can not confirm this possibility.

The Delta E 2000 formula is developed from several datasets constructed by estimating the magnitude of colour difference between pairs of surface colour stimuli. Visually identical stimuli were isomeric, i.e. had identical spectral reflectance functions, and would match to all observers independently of their colour matching properties.

What is the meaning of this? Perhaps this means that when we do asymmetric cross-media colour matches *the inter-observer variation is not determined by observer metamerism*. At least this seems to be so for matches between LCD and CRT computer displays and paint samples as used in our study. The similarity between the prediction of the ΔE_{00} colour difference formula and our results may suggest that in soft-proofing conditions, colour discrimination mechanisms are more dominant than colour matching ones, rendering the phenomenon of observer metamerism less significant than in the conditions of a classical colour matching experiment. The consequence is that any model of uncertainty of colour matching based on variability of colour matching functions (such as the CIE Standard Deviate Observer) would fail when applied to soft-proofing. Descriptions of visual mechanisms governing the comparison of spatially separated stimuli should lie at the basis of any model applicable for such a case. It was reported [37] that the ability of observers to discriminate spatially separated colours is remarkably good, and it is not likely to be mediated by retinal processing but by higher order ones. These mechanisms are yet to be understood. The practical implications of inter-individual variability which is not the result of observer metamerism remains unclear.

Conclusions

During the past century, failures of colorimetric additivity and observer metamerism have been studied extensively, and a significant amount of theoretical knowledge has been accumulated. The application of this knowledge to practical colorimetry, however, has been, and still is, very limited.

In their classical textbook "Colour Science" [10], Wyszecki and Stiles write (p. 280): "*Whether the members of the equivalence set satisfy any form of linearity law can be decided only empirically for the equivalence experiment and observer in question*". This statement can be generalised for the broader case of colour matching: do rules which apply in the conditions of quasi-symmetric matching in classical colour matching experiments apply in conditions in which colorimetry is applied in industry? For additivity and observer metamerism in conditions of soft-proofing, the present report gives a negative answer.

Any change and improvement in colorimetry has to be governed by practical requirements. Do such requirements exist for the two phenomena discussed herein? Unfortunately, very little

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[†] The original data is for 49 observers; two observers were excluded from the analysis due to missing entries

[‡] The authors wish to thank P. Trezona for providing the set of original NPL colour matching data.

published evidence exists. From the results of present study, anecdotal evidence and personal experience, the answer is perhaps positive for additivity failure and negative for observer metamerism – at least as far as soft-proofing is concerned.

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Alan Robertson retired in 2000 after spending 35 years at the National Research Council of Canada working on colour science and metrology. He is a former President of the International Color Association and Vice President of the International Commission on Illumination. He received his Ph.D. in 1965 from the University of London where he studied under David Wright. He currently acts as a consultant to the Colour & Imaging Group of the University of Leeds.