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TECHNICAL REPORT

A REVIEW OF CHROMATIC ADAPTATION TRANSFORMS

CIE 160:2004

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Descriptor: Colorimetry
Colour vision

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The International Commission on Illumination (CIE) is an organisation devoted to international co-operation and exchange of information among its member countries on all matters relating to the art and science of lighting. Its membership consists of the National Committees in 38 countries and one geographical area and of 4 associate members.

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4. To prepare and publish standards, reports and other publications concerned with all matters relating to the science, technology and art in the fields of light and lighting.
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2. D'élaborer des normes et des méthodes de base pour la métrologie dans les domaines de la lumière et de l'éclairage.
3. De donner des directives pour l'application des principes et des méthodes d'élaboration de normes internationales et nationales dans les domaines de la lumière et de l'éclairage.
4. De préparer et publier des normes, rapports et autres textes, concernant toutes matières relatives à la science, la technologie et l'art dans les domaines de la lumière et de l'éclairage.
5. De maintenir une liaison et une collaboration technique avec les autres organisations internationales concernées par des sujets relatifs à la science, la technologie, la normalisation et l'art dans les domaines de la lumière et de l'éclairage.

Les travaux de la CIE sont effectués par 7 Divisions, ayant chacune environ 20 Comités Techniques. Les sujets d'études s'étendent des questions fondamentales, à tous les types d'applications de l'éclairage. Les normes et les rapports techniques élaborés par ces Divisions Internationales de la CIE sont reconnus dans le monde entier.

Tous les quatre ans, une Session plénière passe en revue le travail des Divisions et des Comités Techniques, en fait rapport et établit les projets de travaux pour l'avenir. La CIE est reconnue comme la plus haute autorité en ce qui concerne tous les aspects de la lumière et de l'éclairage. Elle occupe comme telle une position importante parmi les organisations internationales.

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1. Ein internationaler Mittelpunkt für Diskussionen aller Fragen auf dem Gebiet der Wissenschaft, Technik und Kunst der Lichttechnik und für den Informationsaustausch auf diesen Gebieten zwischen den einzelnen Ländern zu sein.
2. Grundnormen und Verfahren der Meßtechnik auf dem Gebiet der Lichttechnik zu entwickeln.
3. Richtlinien für die Anwendung von Prinzipien und Vorgängen in der Entwicklung internationaler und nationaler Normen auf dem Gebiet der Lichttechnik zu erstellen.
4. Normen, Berichte und andere Publikationen zu erstellen und zu veröffentlichen, die alle Fragen auf dem Gebiet der Wissenschaft, Technik und Kunst der Lichttechnik betreffen.
5. Liaison und technische Zusammenarbeit mit anderen internationalen Organisationen zu unterhalten, die mit Fragen der Wissenschaft, Technik, Normung und Kunst auf dem Gebiet der Lichttechnik zu tun haben.

Die Arbeit der CIE wird in 7 Divisionen, jede mit etwa 20 Technischen Komitees, geleistet. Diese Arbeit betrifft Gebiete mit grundlegendem Inhalt bis zu allen Arten der Lichtenwendung. Die Normen und Technischen Berichte, die von diesen international zusammengesetzten Divisionen ausgearbeitet werden, sind von der ganzen Welt anerkannt.

Tagungen werden alle vier Jahre abgehalten, in der die Arbeiten der Divisionen überprüft und berichtet und neue Pläne für die Zukunft ausgearbeitet werden. Die CIE wird als höchste Autorität für alle Aspekte des Lichtes und der Beleuchtung angesehen. Auf diese Weise unterhält sie eine bedeutende Stellung unter den internationalen Organisationen.

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This Technical Report has been prepared by CIE Technical Committee 1-52 of Division 1 "Vision and Colour" and has been approved by the Board of Administration of the Commission Internationale de l'Eclairage for study and application. The document reports on current knowledge and experience within the specific field of light and lighting described, and is intended to be used by the CIE membership and other interested parties. It should be noted, however, that the status of this document is advisory and not mandatory. The latest CIE proceedings or CIE NEWS should be consulted regarding possible subsequent amendments.

Ce rapport technique a été élaboré par le Comité Technique CIE 1-52 de la Division 1 "Vision et Couleur" et a été approuvé par le Bureau de la Commission Internationale de l'Eclairage, pour étude et emploi. Le document expose les connaissances et l'expérience courantes dans le domaine particulier de la lumière et de l'éclairage décrit ici. Il est destiné à être utilisé par les membres de la CIE et par tous les intéressés. Il faut cependant noter que ce document est indicatif et non obligatoire. Il faut consulter les plus récents comptes rendus de la CIE, ou le CIE NEWS, en ce qui concerne des amendements nouveaux éventuels.

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A REVIEW OF CHROMATIC ADAPTATION TRANSFORMS

SUMMARY

This report reviews a number of studies on chromatic adaptation. Four different experimental techniques are first described and their pros and cons are analysed. Eight experimental data sets commonly used to evaluate chromatic adaptation transforms are detailed. Thirteen chromatic adaptation transforms are also described and their equations are given in full. Finally, various studies for testing different transformations are reviewed. The results show that there are four possible candidates for future CIE recommendation, CMCCAT2000, CMCCAT97, CAT02 and CIECAT94. Overall four formulae give quite similar performances and the TC members have not found it possible to agree on which if any of the four should be recommended.

REVUE DES FORMULES DE CONVERSION POUR L'ADAPTATION CHROMATIQUE

RESUME

Ce rapport fait le point sur plusieurs études relatives à l'adaptation chromatique. On décrit d'abord quatre méthodes expérimentales différentes, dont on analyse les avantages et inconvénients. L'évaluation des formules de conversion pour l'adaptation chromatique repose sur huit bases de données expérimentales d'usage courant. On décrit aussi treize formules de conversion pour l'adaptation chromatique, en donnant les équations en détail. Enfin, on passe en revue différentes études relatives au test de plusieurs formules de conversion. Les résultats montrent qu'il se dégage quatre formules susceptibles de faire l'objet d'une recommandation CIE à venir: CMCCAT2000, CMCCAT97, CAT02 et CIECAT94. Globalement, quatre formules réalisent des performances assez similaires, et les membres du TC n'ont pas pu parvenir à un accord pour recommander l'une de ces quatre formules.

ÜBERSICHT ÜBER FARBUMSTIMMUNGSTRANSFORMATIONEN

ZUSAMMENFASSUNG

Dieser Bericht beschreibt eine Anzahl von Untersuchungen über Farbumstimmung. Vier verschiedene experimentelle Techniken werden zuerst beschrieben und ihre Vorteile und Nachteile analysiert. Acht experimentelle Datensätze werden benutzt, um die Farbumstimmungstransformationen zu bewerten. Dreizehn Farbumstimmungstransformationen werden ebenso beschrieben und ihre Gleichungen werden vollständig angegeben. Schließlich werden verschiedene Untersuchungen vorgestellt, die unterschiedliche Transformationen testen. Die Ergebnisse zeigen, daß es vier mögliche Kandidaten für eine zukünftige CIE-Empfehlung gibt: CMCCAT2000, CMCCAT97, CAT02 und CIECAT94. Vier ergeben ähnlich gute Resultate, den TC-Mitgliedern war es jedoch nicht möglich, sich auf eine zu einigen, falls eine der vier empfohlen werden sollte.

1. INTRODUCTION

Chromatic adaptation transforms (CAT) are important for many industrial applications including a colour inconstancy index, colour appearance models, the prediction of corresponding colours, and the prediction of the colour rendering of sources. A colour inconstancy index has long been desired by industry for estimating the change in colour appearance with change in illuminant for a coloured product. The key component of this index is a chromatic adaptation transform. In 1999, the Colour Measurement Committee (CMC) of the Society of Dyers and Colourists (SDC) recommended the *CMC 1997 Colour Inconstancy Index, CMCCON97* (Luo et al., 1999), which includes the *CMC 1997 Chromatic Adaptation Transform, CMCCAT97* (Luo & Hunt, 1998a). A colour appearance model is also essential for cross-media colour image reproduction. It is capable of predicting the change in colour appearance under different viewing conditions such as different illuminants, levels of luminance, background colours and different media [e.g. reflection, transmissive and Cathode Ray Tube (CRT)]. The CIE has standardised a model, *CIE 1997 Colour Appearance Model (CIECAM97s)*, for image applications (Luo & Hunt, 1998b; Luo & Hunt, 1998c). The CMCCAT97 is also included in the CIECAM97s for predicting corresponding colours. For illumination engineering, a CAT is also required for predicting the colour rendering properties between a test and a reference illuminant.

More recently, CIE proposed a new colour appearance model, CIECAM02 (CIE, 2004). It is a more accurate and a simpler model than CIECAM97s. Most importantly, it removes some anomalies in the original model. CIECAM02 includes a new CAT, CAT02. A new colour inconstancy index, CMCCON02 (Luo et al., 2003), was also recommended by replacing CMCCAT97 by CAT02.

Chromatic adaptation has been intensively studied by many colour scientists over several decades. The typical study includes psychophysical experiments for accumulating visual data, derivation of transforms based on colour vision theory, and testing the performance of various CATs using different experimental data sets. This report reviews a number of studies and summarises the recent efforts that have been made by the CIE TC 1-52. The terms of reference of this TC were to review the chromatic adaptation transform with a view to make a recommendation. The TC, while agreeing that a standard chromatic adaptation transform would be very useful, was unable to agree on which of the various chromatic adaptation transforms, which have been suggested should be recommended. Basically the members were split as to the purpose of the committee. One group held that to be acceptable as an international standard, a suitable chromatic adaptation transform (CAT) must be theoretically based, while another group held that while such an objective is desirable, it is more important at the present time that a suitable CAT should work as well as possible, even if only applicable to a limited range of conditions. The reasons for the failure to reach agreement are described in more detail in the Appendix to this report. However the committee all agree that the main body of this technical report provides a useful review of the available literature, models currently available and experimental data used to test the models.

Chromatic adaptation is the visual mechanism for adapting to changes in the spectral composition of the radiation from a light source entering the eyes. The typical example is the appearance of a piece of paper, which is seen in daylight, tungsten or fluorescent light. Although these sources are completely different, the appearance of the paper remains the same: white. The reflectance values for a non-fluorescent sample are always independent of the source, but the tristimulus values are usually very different. A simple chromatic adaptation transform takes the tristimulus values for a test specimen under a test illuminant (e.g. CIE standard illuminant A) and calculates the tristimulus values for the corresponding colour under a reference illuminant (e.g. CIE illuminant C or CIE standard illuminant D65). (The corresponding colour, when seen by an observer fully adapted to the reference illuminant, should look the same as the test specimen when seen by an observer adapted to the test illuminant.) Some transforms are based on colour appearance models, and may require extra information to be input. Fig. 1 illustrates the input and output of a CAT. Typically the input data include the tristimulus values of a sample (X , Y , Z) and of a reference white (X_w , Y_w , Z_w) under the test illuminant and the tristimulus values (X_{rw} , Y_{rw} , Z_{rw}) for the reference white under the reference illuminant. Sometimes the luminance of the test adapting field (L_a) in cd/m^2 is

also required. The output data is a corresponding colour described by a set of tristimulus values for a sample (X_c , Y_c , Z_c) under the reference illuminant.

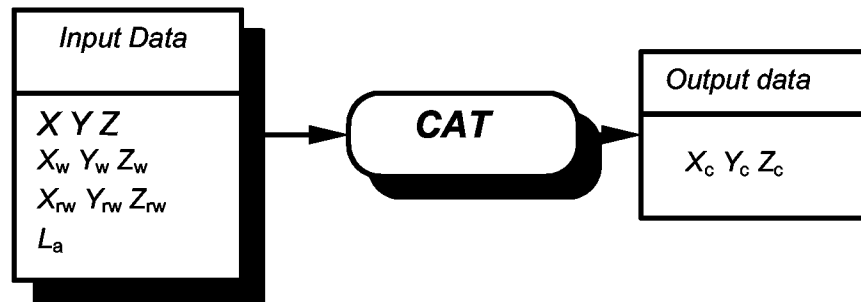


Figure 1. The input and output parameters for a chromatic adaptation transform.

Several types of adaptation affect the colour appearance of object colours. This report is only focused on chromatic adaptation. For more information, readers can refer to some excellent review articles by Bartleson (1978), Wright (1981), Fairchild (1997) and Terstiege (1972).

2. EXPERIMENTAL TECHNIQUES FOR OBTAINING CORRESPONDING COLOURS

Many experimental techniques have been used to obtain corresponding colours for pairs of illuminants. These can be divided into four categories: *haploscopic matching*, *local-adaptation matching*, *memory matching*, and *magnitude estimation*. Several experimental parameters also have significant impact on the experimental results. These are the *contents in the viewing field* (*simple and complex*), and *modes of colour* (*aperture and non-aperture*). In usual situations, we look at objects in a complex viewing field using both eyes. However, a simple field has been widely used, particularly in the earlier experiments, because it simplifies experimental conditions. Even a simple field can have different appearance modes. The aperture mode of colour is defined as a mixture of colour lights perceived as a filled colour hole against a uniform surround. This state of adaptation is vastly different from that using a non-aperture stimulus (typically presented using reflection, transmissive and self-luminous modes such as CRT).

Table 1 lists some of the classical experiments conducted using each of the four techniques. For each experiment, the viewing field, mode of colour and reference number are also given. The experiments marked by an asterisk in Table 1 were chosen to be extensively studied by CIE TC 1-34 on Testing Colour Appearance Models and CIE TC 1-52 on Chromatic Adaptation Transforms.

Table 1. List of classical experiments for each technique.

Viewing Field	Experiment	Mode	Reference
HAPLOSCOPIC MATCHING			
Simple	Wright	Aperture	Wright, 1934
	Hunt	Aperture	Hunt, 1952
	Brewer	Aperture	Brewer, 1954
	Burnham et al.	Aperture	Burnham et al., 1957
	Wassef	Non-aperture	Wassef, 1959
	Bartleson & Breneman	Aperture	Bartleson & Breneman 1967
	Nayatani et al.	Non-aperture	Nayatani et al., 1988
	*Mori et al.	Non-aperture	Mori et al., 1991
Complex	*McCann et al.	Non-aperture	McCann et al., 1976
	*Breneman	Non-aperture	Breneman, 1987
	Fairchild et al.	Non-aperture	Fairchild et al., 1994
LOCAL-ADAPTATION MATCHING			
	MacAdam	Aperture	MacAdam, 1956
MEMORY MATCHING			
Simple	*Helson et al.	Non-aperture	Helson et al., 1952
Complex	*Lam & Rigg	Non-aperture	Lam, 1985
	*Braun & Fairchild	Non-aperture	Braun & Fairchild, 1996
MAGNITUDE ESTIMATION			
Simple	Sobagaki et al.	Non-aperture	Sobagaki et al., 1974
	Pointer et al.	Non-aperture	Pointer et al., 1977
	Bartleson	Aperture	Bartleson, 1979a
	*Kuo et al.	Non-aperture	Kuo et al., 1995
	Xu et al.	Non-aperture	Xu et al., 1997
Complex	*Luo et al.	Non-aperture	Luo et al., 1991a; Luo et al., 1991b
	*Luo et al.	Non-aperture	Luo et al., 1993a; Luo et al., 1993b

Note: The experiments marked by an asterisk were chosen to be studied by CIE TCs.

2.1 Haploscopic matching

As shown in Table 1, haploscopic matching [also called *differential ocular conditioning and comparison* (Bartleson, 1978)] is the most widely used experimental technique. Most of the earlier experiments were conducted using aperture stimuli with a simple viewing field. This technique requires a specially designed viewing apparatus that presents a different adapting stimulus to each of the observer's two eyes. An example is given in Fig. 2, in which an observer viewed from an eyepiece and saw the left field by one eye and the right field by the other eye. After allowing time to adapt, one eye is adapted to CIE standard illuminant D65 and the other to CIE standard illuminant A. The observer is then asked to adjust the stimulus, C2, seen by one eye to match C1 seen by the other eye by altering amounts of red, green and blue lights. The task is relatively simple and the results, in general, have higher precision than the other techniques. However, their validity is dependent on the assumption that the adaptation of one eye does not affect the sensitivity of the other eye. Recent results from Barlow and Mollon (1982) show that when two eyes are presented with two stimuli under different adapting fields, observers tend to bias more towards one field than the other. This is known as *binocular rivalry*. In addition, the technique imposes unnatural viewing conditions together with constrained eye movement.

More recent haploscopic experiments have used non-aperture stimuli with a complex viewing field. Breneman (1987) devised an apparatus with a complex adapting field and allowed observers to use normal eye movement. Fairchild et al. (1994) also developed a new technique: *successive-Ganzfeld haploscopic matching*. The Ganzfeld viewing device was constructed to allow one eye to view the reference adapting field including a reference image or colour patch, while the other eye saw a spatially uniform neutral colour having a close match of luminance and chromaticity as the test adapting condition. After a suitable adaptation time, the process was then reversed by allowing the other eye to view the test adapting field, which includes a pair of images or samples, while the other eye saw a spatially uniform neutral colour having the same luminance and chromaticities as the reference adapting condition. Observers were asked to choose one image or colour giving the closer match to the one previously seen in the reference field. The above two techniques retain some of the advantage and overcome part of the problems occurring in simple haploscopic matching.

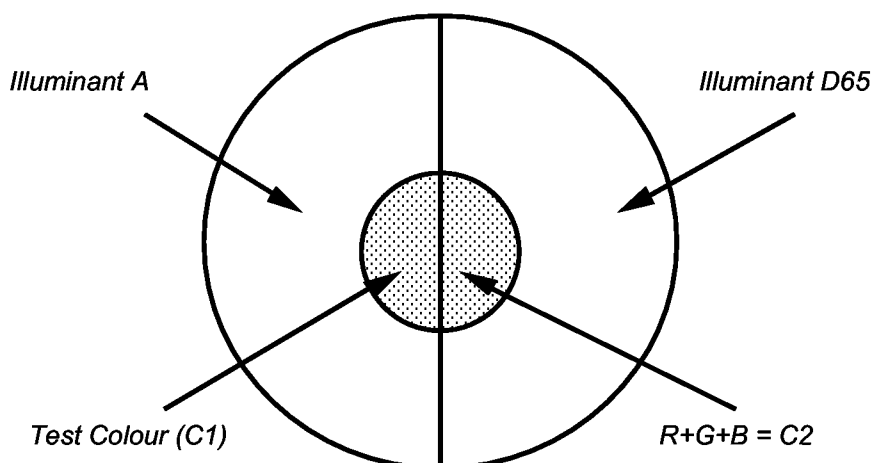


Figure 2. A typical viewing condition used in the haploscopic matching experiment.

2.2 Local-adaptation matching

MacAdam (1956) derived a technique to obtain corresponding colours, in which differential retina conditioning was used. In this method, two different areas of the retina in the same eye were exposed in the two halves of the visual field for colour matching.

He built a 10° visual colorimeter in which two halves of the fields were filled with different adapting stimuli. Every 10 seconds, for 1 second only, a test stimulus replaced the adapting stimulus in one-half of the field and an adjustable stimulus in the other half of the field. Observers were asked to make a colour match between the test and adjustable colour in that 1-second interval. Again, similar to haploscopic matching when the two eyes may interact with each other, it is possible that the two parts of the retina affect each other.

2.3 Memory matching

Memory matching is carried out under normal viewing conditions using both eyes and without the interposition of any optical devices. All experiments (Helson et al., 1952; Lam, 1985; Braun & Fairchild, 1996) have been conducted using object-colour stimuli. This technique provides a steady state of adaptation with free eye movement. Observers are first trained using a colour order system (say Munsell) until they are very familiar with its scales (Munsell value, chroma and hue in this case). This means that they are able to describe with reasonable accuracy and precision the colour of any object in these terms under any viewing conditions. For example, the observers of Helson et al. (1952) were asked to fully adapt under CIE illuminant C, and presented with a sample in a viewing cabinet illuminated by CIE illuminant C. Each observer estimated the Munsell hue, value and chroma. The experiment was performed with many samples and repeated under CIE standard illuminant A. Suppose that for one sample, the results were 5R 4/4,5 for CIE illuminant C and 5R 4/5 for CIE standard illuminant A, i.e. the sample appeared more colourful under CIE standard illuminant A. To form a pair of corresponding colours, the measured values (XYZ) for CIE illuminant C