Description and Evaluation of the Variability of Human Color Vision in an Anti-piracy Context

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Abstract

In the context of anti-piracy / anti-camcorder in digital cinemas a major requirement is invisibility of inserted pattern for the legal viewer watching the main cinema screen. On the basis of a multispectral projection system developed to create color metamers, we faced the need to explore and understand better color vision variability.

This paper first presents the application context and the problem to solve. Then the CIE-2006 model is introduced, complemented with a brief overview of genetic aspects of color vision, as these were the basis for the study. Variability of color vision is then evaluated, first on a set of Stiles and Burch observers and then on observers in our digital cinema context.

Two experiments are then presented, incremental steps towards the system improvement. The two experiments reveal coherent disparities for the different observers, modeling these disparities as L- and M- cone fundamentals shifts. The improvement between the first and the second experiment is shown in terms of closeness to a standard observer.

This gain is a clear result of integrating color perception knowledge in the system design. It is as well a definite step towards acceptance of the metamer images by a wide and varied population of cinema observers.

Introduction

According to the Motion Picture Association of America [MPAA], Hollywood loses billions of dollars a year on unauthorized copies of movies. Among all forms of piracy, illegal camcording in a theatre represents one major threat. Pirate DVD, using camcorded bootlegs, can be found on the black market soon after the release of a movie.

While other techniques exist for prevention of unauthorized copying by camcorder, the approach followed here is to introduce techniques damaging the quality of the captured movie (as in [1]). This "anti-camcording" technology has strong requirements:

- It must be transparent to legitimate viewers in the theatre; from color experts ("*golden eyes*") to color blind viewers. The technology cannot introduce any perceptible artifacts into the content.
- The visible effect on a camcorder copy must be disturbing enough to discourage the pirate. For high quality captures it may be sufficient to introduce an "illegal copy" message that is difficult to remove, but for low quality captures the degradation must be more severe.
- It must affect all camcorders.

The technical approach we have chosen is called the metamerism approach where differences between how a camcorder and the human eye process color are exploited. The metamerism effect is the capability of the eye to perceive the same color even if two visual spectra that generate this identical perception are different. In other words, we can create the same yellow perception for the eye with a 3-primary projector (RGB) or with a 4-primary projector (RGB + Cyan primary for instance). On the other hand, camcorders have only three sensors (RGB) with fixed sensitivity responses curves. In general, they do not exactly "perceive" the same color as the human eye.

Figure 1. *Anti-camcording context*

The basic approach is to display part of the picture with a first set of primaries and the rest with a second set such that the eye will perceive the desired color and the camcorder will get a disturbed picture.

As explained before, the primary challenge is transparency for the rightful audience. As this method relies on color perception, it's variability among a population must be considered. Color blindness introduces an interesting sub-population but we focus on this paper on the variability of the human color vision in general for people considered as "normal viewers" (non-anomalous trichromats).

Problem to solve

For our discussion, the following two terms need to be defined (see figure 2):

- ***Illuminant metamerism***: (very) different spectra resulting in the same perceived color for a given Observer A.
- ***Observer metamerism***: two spectra perceived as identical for Observer A but perceived as different by Observer B.

The notion of perceived color refers here to L- M- S- "cone fundamentals" response.

The developed anti-camcorder system uses *illuminant metamerism* between color pairs to allow for pattern insertion in the image signal. Thanks to this specifically generated metamerism, the pattern is invisible for a "human observer", but visible for a camcorder acquisition, as it has different spectral integration.

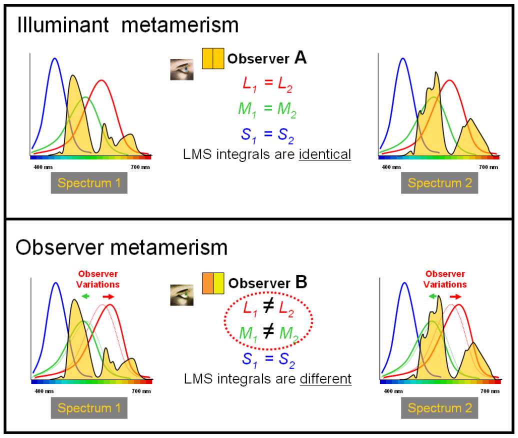


Figure 2. *Illuminant and Observer metamerism*

In the first version of the anti-camcorder system the "human observer" was assumed to match the vision parameters of a "standard observer". Some adjustments had been done, integrating as well anomalous trichromats and dichromats' characteristics [2].

The result has been a good invisibility for only some observers in the cinema, while a majority could see the pattern clearly or perceive annoying artifacts. Undoubtedly *observer metamerism* was an issue.

In the second version, observer metamerism as described by CIE-2006 [3] has been integrated into the system design, adjusting spectrally metameric color pairs. This resulted in a much wider acceptance among observers, but still a number of them (~2%) could detect the inserted patterns.

At that stage, the technical problem to solve was to go beyond the CIE-2006 {Age + Field Size} model, seeking solutions in directions recommended in the "*1.3 Restrictions*" paragraph of [3] as identified by authors. Most specifically, an important source of variability put forward was the polymorphism of photopigments, creating displacement of a few nanometers of the cone fundamentals. These genetics aspects, as detailed in [4], can be explored to complement CIE-2006.

Goal of the paper

The goal of this paper is to present work done to address the metameric pattern visibility issue for digital cinema observers watching the theatre screen. The prospect is to better understand variability in color perception in order to design future versions of the system, beyond CIE-2006 model performances. In cinema context there is undoubtedly the need that a very large majority of observers cannot detect the inserted pattern in the direct viewing conditions.[1]

We need to take into account the variability of human vision, including the difference in spectral absorbance of macular pigment and of ocular media as well as the genetic aspects of vision.

[1] It should be understood that this paper does not address the difference between the direct view -legal- perception of the inserted pattern and the visibility of this pattern on the pirate's copy, which, in practice, is much higher in contrast.

First the CIE-2006 model is presented, with, as complement, a rapid description of genetic aspects. In the second step, an analysis is presented on the basis of 20 Stiles & Burch observers[2]. Then, tests in Digital Cinema conditions are presented comparing two solutions: a first solution designed only for a "standard observer" and a second solution addressing color vision variability.

As in other applications, the anti-camcorder system involves the observation of color metamers to operate. It is the goal of this paper to explain that a good correspondence can only be achieved considering human color perception variability from the design stage.

Color perception variability: base models

CIE-2006 model

Observer metamerism has been addressed by the CIE (Commission Internationale de l'Éclairage) in its work, resulting in its technical report [3] published in 2006. This report defines two reference observers (2° and 10°) as the basis for the computation of 'standard' cone fundamentals for a continuum of observers in different conditions. Two parameters are available: field size between 1° and 10°, and age between 20 and 80. The reference observers were adapted / derived from the 10° Color Matching Functions (CMF) of Stiles and Burch (1959) [5] taking into account Stockman and Sharpe (2000) recommendations [7]. The model takes into account the spectral optical density of the macular pigment, of the lens and other ocular media, and the peak optical density of the visual pigments. Their dependence upon age and field size has been studied and modeled. The reader can refer to CIE publication [3] concerning the model assumptions, restrictions and details.

Figure 3 gives a view of the age variability from 20 to 80 at a fixed field size, 10°.

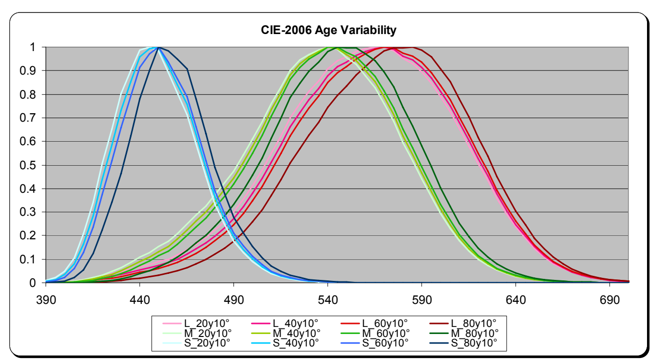


Figure 3. *CIE-2006 model: age variability*

Figure 4 gives a view of Field size variability, according to CIE-2006 model, from 1° to 10° for an age of 40.

[2] The individual functions of 20 Stiles & Burch observers have been published in [6].

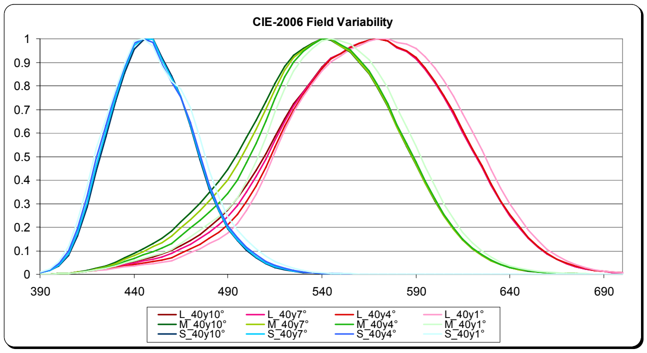


Figure 4. *CIE-2006 model: field variability*

Genetics

Human color vision is trichromatic, based on three types of retinal photoreceptor called cones. These cones are characterized by their respective spectral sensitivities corresponding to the probability for a photon of a given wavelength to be absorbed. The three types of cones have been named L, M and S cones standing respectively for Long, Medium and Short wavelength sensitivity. They can also be described by their wavelength of maximum absorbance (λ_{max}), respectively close to 440 nm for S, 545 nm for M and 565 nm for L.

The presence of three different receptors is generally explained by a genetic evolution of the human vision system allowing the primate to be better adapted to his environment. The red-green differentiation is described as to be the last one occurred during this evolution, only several million years ago. This could be the reason why the difference between the genetic composition of L-cone and M-cone is quite small. There are only 15 different codons[3] out of 364 between L-cone and M-cone pigment genes, and among these only some 15 could be responsible for a spectral sensitivity change. During meiosis, hybrid cones can be created, with spectral sensitivity in between L-cone and M-cone sensitivity. This may create color deficiency, whose severity will depend on the similarity between the hybrid cone and the original one (L or M-cone).

Furthermore, besides these color blindness cases, the genetic composition of L-cone and M-cone are not strictly the same. Even people without color deficiency have different genetic composition of their cone photopigments. For instance, some have serine amino-acid at position 180 of their L-cone photopigment opsin gene, while others have alanine.

This Serine/Alanine polymorphism of the L-Cone photopigment can be taken as a common example of variability. It leads to a substantial variation in spectral sensitivity for the long wavelengths, sometimes approximated as a shift of 4 nm or more of the wavelength of maximum absorbance. Different studies [7][8][9] have shown that human L-cone pigment genes can have serine or alanine in a more or less equivalent proportion. Depending on the world area, this proportion can vary but both types are always present in a population. This leads to a substantial variability in color perception.

This Serine/Alanine polymorphism is not the only one reason for color perception variability in the general population. Cone density in the retina, macular pigment optical density, etc, also contribute to slightly different sensitivities from one observer to the other. Each individual color perception is actually a combination of different variations around an average value as defined in CIE-2006.

A few nanometers in peak sensitivity position or cone fundamental shape variations are not enough to be detectable easily and one cannot know simply to which group he/she belongs to. Nevertheless, this difference is really noticeable in our results.

Analysing Stiles & Burch 20 observers

The goal of this paragraph is to evaluate if two groups may be identified in the 20 Stiles and Burch selected observers as used in the CIE-1964 standard. Here follows an analysis with simple assumptions in that direction.

The start is from the 20 Color Matching Functions of Stiles and Burch equalization experiment as shown on figure 5. In this experiment, each observer had to equalize test stimuli using a mixture of three primaries.

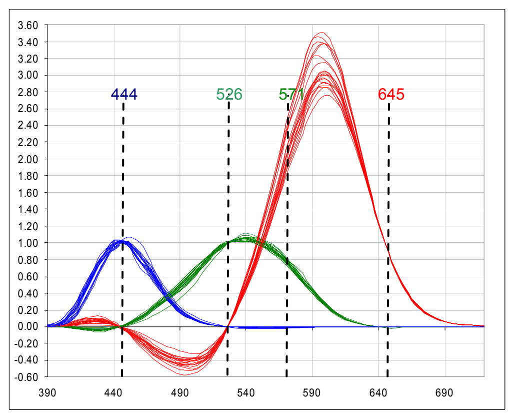


Figure 5. *RGB matching functions for the 20 Stiles & Burch observers*

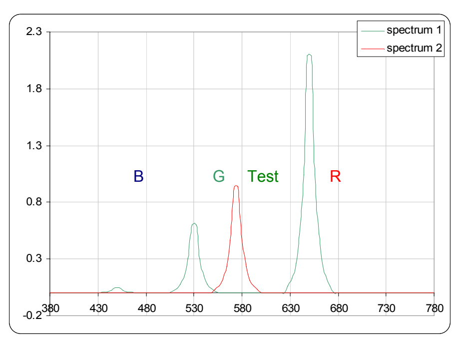


Figure 6. *Equalization sources spectrum estimates*

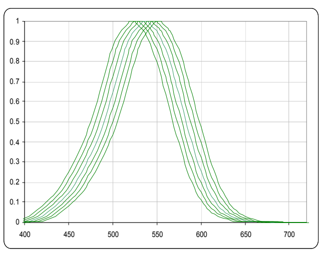
[3] A codon is a triplet of RNA or DNA bases that represents the code for a single amino acid.

In this analysis, the test stimulus at 571 nm is chosen (red curve, spectrum 2, in figure 6), for which each observer adjusted R, G and B of the primary stimulus (green curves, spectrum 1, in figure 6).

As the actual spectra were not known to us, for this computation, we use a spectrum model for the matching experiment sources. This spectrum model is of bandwidth 10 nm and its form factor is shown on figure 6 for the 4 source colors used, at different power levels. As in the original experiment, the test color is centered at 571 nm and the 3 primaries are centered at 645 nm, 526 nm, and 444 nm respectively for Red, Green and Blue.

Knowing now the color matching functions of figure 5, we can evaluate what were the levels of the primaries chosen by each observer. This is done by computing and equalizing the stimuli of the 571 nm test patch with the primary stimuli adjusting the power of each primary. At that point an estimate of the matched spectra is available to us.

From this point, knowing the test stimulus spectrum estimate and the matched primaries spectrum, we can compute what shift should be applied to the CIE-2006 curves L & M to match perfectly in the L, M, S space. The L & M fundamentals affected by shifts of 5 nm are presented in figures 7 & 8.



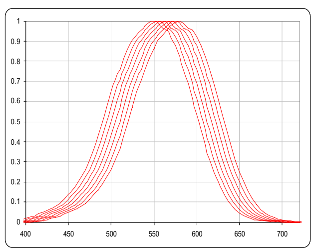
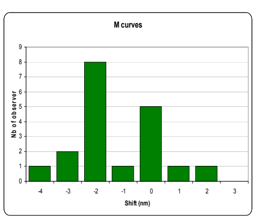


Figure 7. and Figure 8. *Shifted M and L fundamentals*

For each Stiles & Burch observer we obtain a value of shift for L & M; the bar-graphs presented in figure 9 & 10 give the number of observers showing a given shift in the M- fundamental shifted curves (figure 9) and in the L- fundamental shifted curves (figure 10).



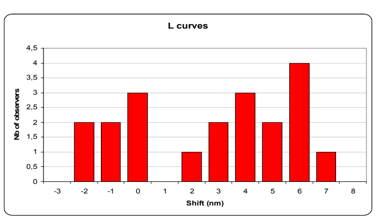


Figure 9. and Figure 10. *Correspondence counts for M and L shifts*

We can also present the data as a 2D graph (see figure 11); even with the low number of observers we can easily see two groups in the population; the shift between the two groups is about 6 nm for the L cones.

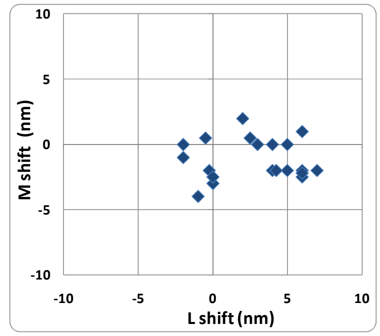
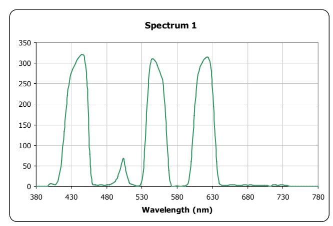


Figure 11. *2D plot of S&B observers matching L and M shifts*

Digital Cinema tests

In order to make some tests of multi-primary system, a Christie CP2000 digital cinema projector was modified. A color wheel system, such as the one designed by Dolby to generate a 3D picture, is installed inside the projector in the illumination light path, between the lamp house and the optical engine. It allows displaying sequentially 2 different spectra at 144Hz frequency. This setup gives two different sets of primaries (R1,G1,B1 and R2,G2,B2) to generate a given color. The first system of primaries that we defined (called CW1 = Color Wheel 1) is shown in figure 12 and 13. Metameric colors were obtained by calculating the right weight for each primary of each spectrum.



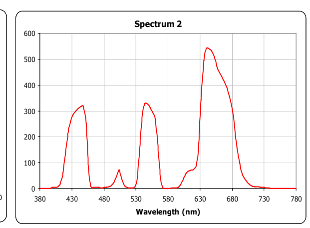


Figure 12 and Figure 13. *Spectrum 1 and 2 of CW1*

Any color K was then reproduced by specifying the α1, α2, β1, β2, γ1, γ2 parameters in the following equation.

$$K = \alpha1 * R1 + \alpha2 * R2 + \beta1 * G1 + \beta2 * G2 + \gamma1 * B1 + \gamma2 * B2$$

Several perception tests were conducted using this system. The first test we made was to evaluate the perceptibility observers have with two metameric colors (metameric in the sense of CIE-2006). We defined a static picture with 2 different areas as follow:

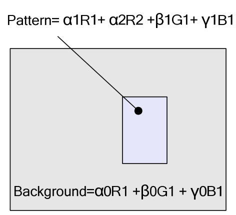
Area 1:

3-primary Background = α0*R1 + β0*G1 + γ0*B1

Area 2:

4-primary Pattern = α1*R1 + α2*R2 + β1*G1 + γ1*B1

Figure 14 represents the pattern we used and the table of figure 15 gives results obtained with different observers when they adjusted the R1, G1, B1, R2 weights. Note that there were no color blind people in this group (as validated with a Heidelberg-Multi-Color Anomaloscope).



Background	R1	G1	B1	R2
	544	544	544	0

Pattern	R1	G1	B1	R2
Th-BP	128	584	544	1023
Th-BL	75	604	544	1023
Th-TS	90	586	544	1023
Th-DD	135	584	544	1023
Th-MP	105	589	544	1023
Th-SJJ	81	602	544	1023
Th-GH	88	597	544	1023
Th-VJR	272	554	544	1023
Th-JE	112	584	544	1023
Th-KJ	87	596	544	1023
Th-VJF	37	688	544	1023
Th-SA	95	586	544	1023

Figure 14. and Figure 15. *Test pattern CW1 and observer results*

Figure 16 shows the evaluation of the shift of L and M curves4 for each observer compared to CIE-2006 model with respect to the age of the observers (known in our case). We apply here the same principle as the one used in the previous section for Stiles and Burch observers.

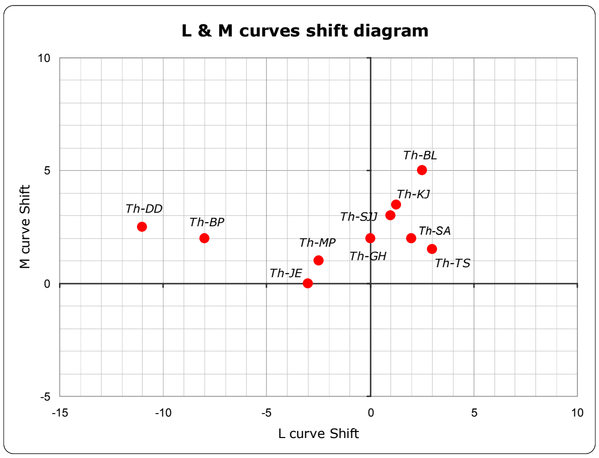


Figure 16. *2D plot of CW1 observers matching L and M shifts*

The first conclusion is that the variability is a reality and one cannot really speak about metameric colors in a general sense. It is an observer dependent experience. Compared to the CIE-2006 model, we need to shift curves to make them fit with each observer. This is in line with the genetic model of variability.

Nevertheless, it is clear that the choice of the G1 primary (green of the Spectrum1) was not adequate. The variability of the macular pigment is so high in this range of wavelengths that it clearly increases the global variability of the system. The related perception of people reflects also this macular pigment variability and not only the one due to L and M cones.

A second version of the color wheel (CW2) was defined to be more independent of macular pigment variability. Spectra of this color wheel are shown in figure 17 and figure 18.

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[4] Influence of the short wavelengths (S-Cone) was cancelled out in this study and experiment.

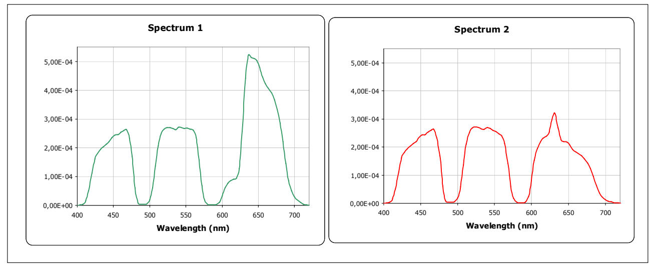
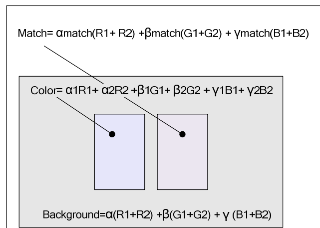


Figure 17 and Figure 18. *Spectrum 1 and 2 of CW2*

A second test pattern was created to evaluate the remaining visibility with 3 different test zones (see figure 19 & 20):

Color level is calculated to have the same metameric color as the background using the R1, R2, G1, G2, B1 & B2 primaries. As before, the metameric colors are based on the L, M, S CIE-2006 model. Parameters of the right area (called the "Match" area) are fully controlled by the observer, with R, G, and B levels acting in the same way as for the background primaries. With this method, a "standard" L, M, S observer sees no difference between the background and the left sample, and so he/she does not need to modify the "Match" area. A "non standard" observer adjusts the R, G, B levels of the "Match" area to give his/her vision of the left color.



Color	R1	G1/G2	B1/B2	R2
	41	118/70	51/51	255

Background	R1	G1/G2	B1/B2	R2
	111	93/93	51/51	111

Match	R1	G1 &G2	B1 &B2	R2
Th-BP	108	93	51	108
Th-BL	115	92	51	115
Th-TS	114	93	51	114
Th-DD	108	93	51	108
Th-MP	111	92	51	111
Th-SJJ	111	93	51	111
Th-GH	111	93	51	111
Th-JE	109	93	51	109
Th-KJ	115	93	51	115
Th-SA	114	93	51	114

Figure 19. and Figure 20. ***Test pattern CW2 and observer results***

The same set of observers as for CW1 was selected for the second test with CW2. Knowing respective spectra, the same L and M shifts were used to evaluate the observers' vision. Figure 21 illustrates the respective L/M shift estimates for each observer. Evidently, observers have the same overall L and M variations compared to CIE-2006. Tests with CW1 and CW2 practically reflect the same observer variability. Each observer is at a similar relative position in each of the two diagrams.

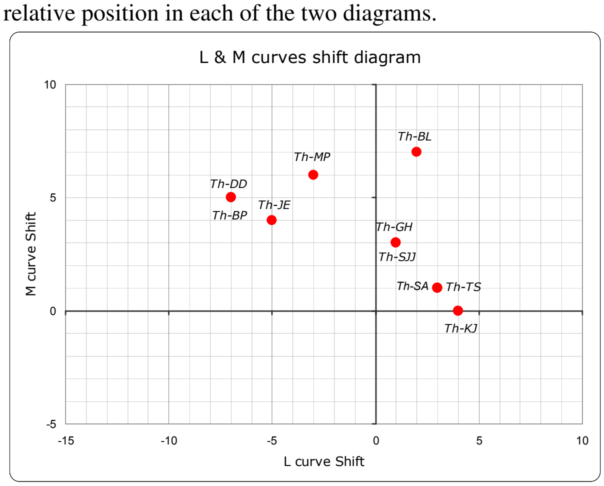


Figure 21. *2D plot of CW2 observers matching L and M shifts*

In CW1 and CW2 tests, we followed the same goal, trying to evaluate the real perception of the metameric colors generated by the anti-camcorder system. In both cases we found a significant variability among the selected population. This variability has the same order of magnitude in the two situations, and positive/negative L/M shifts for the large majority of observers can be identified to be in coherence (see figure 16 and 21).

Identifying the inter-observer variability was the first step in our work. The goal of designing the second color wheel was to further improve the metameric effect acceptance and pattern invisibility on the main screen keeping a disturbing effect on th camcorder.

In order to measure this effect for each color wheel spectra, we calculated the stimuli[5] error between the L and M cones of the CIE-2006 observer and each of the real observers. These values are absolute values as shown in figure 22.

Error stimuli CW 1 en %			Error stimuli CW 2 en %		
	L	M		L	M
Th-BP	2.28	0.84	Th-BP	0.70	0.09
Th-BL	0.54	1.60	Th-BL	0.07	0.68
Th-TS	0.82	1.22	Th-TS	0.92	0.45
Th-DD	2.88	0.84	Th-DD	0.70	0.09
Th-MP	0.74	0.95	Th-MP	0.29	0.14
Th-SJJ	0.19	1.52	Th-SJJ	0.10	0.24
Th-GH	0.89	0.41	Th-GH	0.10	0.24
Th-JE	0.90	1.00	Th-JE	0.29	0.14
Th-KJ	0.21	1.20	Th-KJ	0.93	0.14
Th-SA	0.43	1.14	Th-SA	0.92	0.46

Figure 22. *Error percentages on L and M for CW1 and CW2 comparing real observers to a standard observer*

Clearly the errors are much lower for the CW2, indicating a significant improvement over the first version of the system. Since our application is to generate a metameric effects as invisible as possible, the CW2 was clearly more efficient in this regard.

Nevertheless the observer variability still exists, and the remaining visibility of inserted messages in the video is still annoying in some circumstances and for some observers. The next step will be to further refine the spectral definition in order to even better accommodate the range of variability in the human color vision system so as to maximize the acceptability of the metameric colors among the observers.

Conclusion

In the field of the anti-piracy in motion pictures, we have developed a complete multi-primary system prototype to exploit the principle of metamerism to jam a camcorder in a theatre. Main issue in this approach was to cope with the human vision variability. In this paper, we presented the context of the study and the results of tests made in digital cinema environment. Beyond variability related to the field size and age of the observer as described in CIE-2006 model, we have identified a significant variability between observers. The consequence for our anti-piracy approach is important. The invisibility required on the main screen means that we need to compensate for this variability. Building on this previous work, the next step is to define the appropriate spectral characteristics of the system that is able to generate metameric colors for an even broader observer population.

5 Spectrum 1 vs. Spectrum 2 integrals for L and M cone fundamentals for CW1 and CW2

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Authors Biography

Didier Doyen is graduate engineer of the Institut National des Sciences Appliquées in Rennes (1989). He joined Thomson in 1990 where he was involved in signal processing activities. He drove projects aiming at improving the picture quality of different technology of displays and more recently projects related to anti-piracy in digital cinema environment. This last activity required a study of the human color vision system to better understand its consequences in term of color perception.

Jean-Jacques Sacré is graduate technician of the "Institut Universitaire de Technologie » of Angers (1972). He joined Thomson in 1974 and has worked on the industrialization of the first color television cameras. During this period he specialized in optics (training at the "Institut d'Optique" of Orsay) and during the 80's-90's worked on new sensors technologies and displays; he became engineer in 1995 and *participated in several research projects as for example Anti-Camcorder for cinema application.*

Laurent Blondé is graduate engineer of the Institut d'Optique (1985). Hired as a research engineer for THOMSON R &D, he participated in more than a few R&D projects including: Infrared Image Synthesis, Special Effects and Virtual Studio, Display processing, Anti-Camcorder and Color Management for Cinema applications. Supporting both the Technicolor and Grass Valley businesses, Laurent Blondé is currently a Technical Advisor. His research interests involve all domains of image processing and synthesis for the media industry.