

Modeling the Appearance of Fluorescent Colors

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The advent of improved durability pigments has resulted in the increased use of fluorescent colored materials in safety and warning applications (e.g., high-priority traffic signs; safety vests). Yet, little is known about the relationship between the visual effectiveness of fluorescent colored materials and their photometric properties. Archival data sets were reanalyzed to assess the appropriateness of an elegant psychophysical model of the appearance of fluorescent colors first introduced by Schultze (1953). The results indicated that the expression *Y/MacAdam Limit* (x,y) provided an excellent prediction of the suprathreshold appearance of fluorescent color (x,y); where (x,y) represented the color of the test stimulus in 1931 CIE chromaticity coordinates. These findings have important implications for design using fluorescent colors and may also contribute significantly to our understanding of related color phenomena.

Introduction

Fluorescent colored materials exhibit many properties that contribute to enhanced visual performance. They can be engineered to be considerably brighter than their non-fluorescent counterparts yielding a class of stimuli that are simultaneously capable of supporting both high luminance contrast and high color contrast with the surrounding environment. Yet, despite these ideal optical characteristics, fluorescent colored materials have historically enjoyed only limited use in many safety applications. The primary reason for this under utilization of fluorescent colored materials in safety and hazard marking/warning applications can be attributed to the "durability problem". That is, the traditional *organic* pigments used to generate fluorescent colors quickly degrade when exposed to sunlight. A vivid fluorescent orange sign constructed using organic pigments would fade to white following just a few months of exposure to the elements. However, during the past 20 years, technological advances have resulted in the development of durable fluorescent pigments that maintain their vivid coloration for 7-10 years under normal exposure to the sun. These advances have resulted in a proliferation of fluorescent colored safety and warning products with enhanced visual conspicuity. This accelerated growth in the use of fluorescent colors in safety and warning applications has also resulted in an increased interest in the psycho-physical factors influencing the appearance of fluorescent colors. This paper provides an overview of the physical basis of fluorescence and tests a simple psychophysical model relating the photometric properties of a fluorescent colored stimulus to the magnitude of its perceived luminosity (i.e, fluorescent appearance).

Fluorescent Emission

Fluorescent photopigments contain molecules that absorb short wavelength light. However, rather than converting

this light energy to heat, it is re-emitted as light at some lower energy (longer) wavelength. This conversion process is very rapid (typically 10^{-8} s or less); distinguishing fluorescence from phosphorescence - its much slower counterpart (Burns, et al., 1995). As such, fluorescent materials do not "glow in the dark". Fluorescent emission only occurs while the pigment is being irradiated by light of the appropriate wavelength. The absorption-emission spectrum for a typical fluorescent pigment is shown in **Figure 1**.

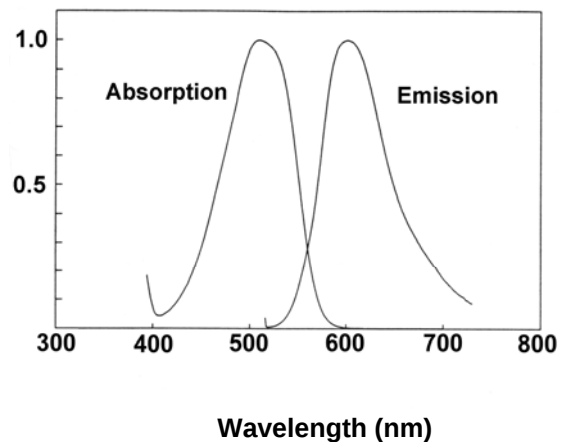


Figure 1. Absorption-emission spectra for typical fluorescent pigment

In the past, organic pigments were commonly used in the production of fluorescent colored materials. These pigments typically absorbed invisible ultraviolet (UV) light (wavelengths less than 400 nm) and re-emitted light somewhere in the visible spectrum (400-700 nm). Such organic materials can not take advantage of UV-protective coatings typically used to enhance daylight durability of colored surfaces since they rely upon the availability of UV

light to source their fluorescent emissions. Thus, organic fluorescent pigments tend to quickly degrade with continuous exposure to natural sunlight. More technologically advanced *inorganic* pigments are now readily available that source their fluorescent reactions using visible (400-440 nm) light. These inorganic materials can be protected from the destructive rays of the sun with simple UV coatings that dramatically improve their long-term durability.

Minimum Luminance Required to Yield Fluorescent Appearance

Highly fluorescent materials give rise to a unique sensory experience known as *farbenglut* (color glow) or *fluorence* (the psychological analogue of fluorescence). Fluorescent materials appear as "reflective surfaces" (rather than "light sources") with an "unnatural" (or synthetic) vividness and/or colorfulness. However, the precise nature of the visual experience associated with fluorescent colors has remained largely unexplored. This lack of systematic investigation is probably due to the complexity of the phenomenon itself as well as the difficulty associated with specifying and manipulating the relevant stimulus parameters (see Fairchild, 1998). An exception to this state of affairs can be found in the programmatic work of Evans (1959; 1974). Evans developed a paradigm and a metric for assessing the quantity of narrow-band light that had to be added to an isolated color stimulus (viewed against an achromatic surround of constant luminance) in order for it to yield a "just noticeable" experience of fluorence. The quantity of "added luminance" needed to reach the fluorence threshold varied as a function of stimulus wavelength (as depicted in **Figure 2**).

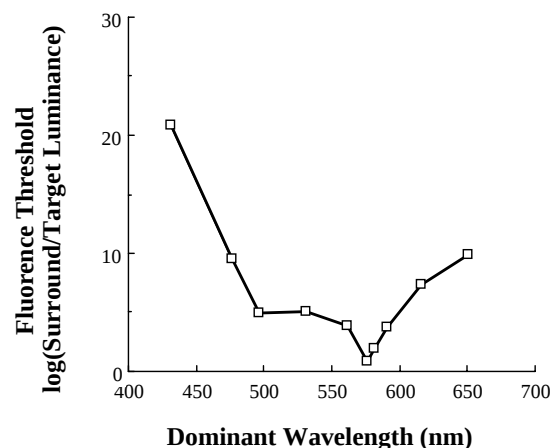


Figure 2. Fluorence threshold as a function of stimulus wavelength (Data from Evans, 1974; achromatic surround)

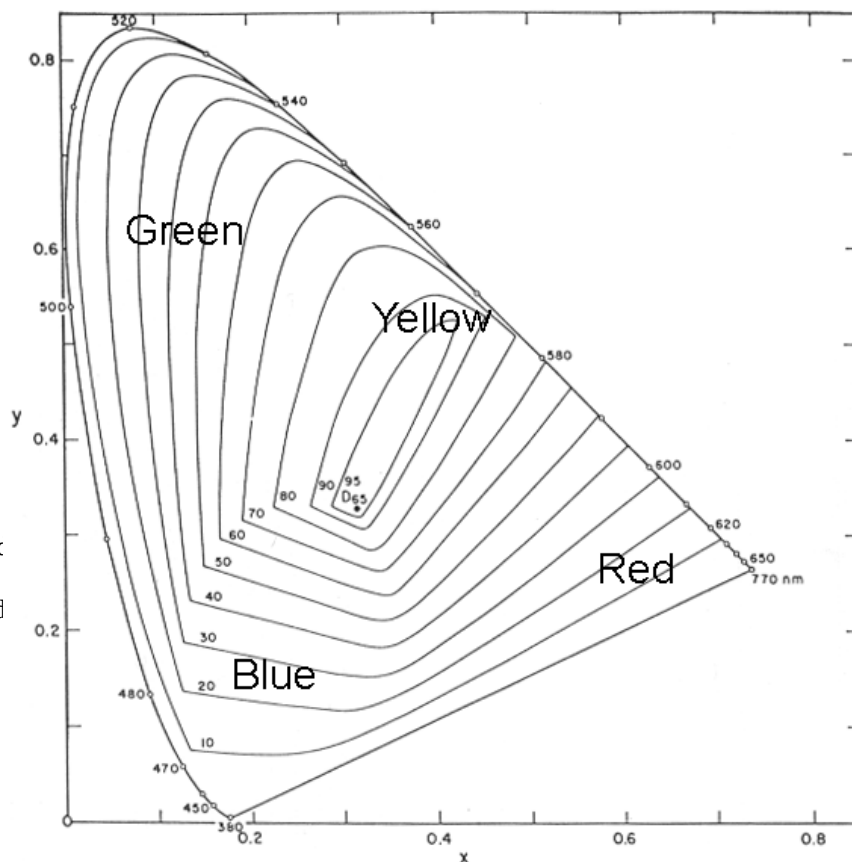
When the "added luminance" continued to be incremented above the level of the threshold for fluorence the appearance of the test stimulus would eventually give way to a shift from the perception of a "reflective surface" to the

appearance of a "self luminous" object. It is of special note that this 2nd threshold marking the transition from "surface mode" to "illuminant mode" perception (1) also varied systematically with stimulus wavelength in a manner similar to the fluorence threshold and (2) always occurred at a luminance level below that of the achromatic surround.

Modeling Suprathreshold Appearance of Fluorescent Colors

Schultze (1953)¹ proposed -- but did not test -- a psychophysical model that appears to predict Evans' work with fluorence thresholds and that may provide an initial basis for scaling suprathreshold fluorence appearance.

Schultze's model begins with the notion that the maximum luminance of any "colored" surface is strictly limited to some fraction of that attained by a reference "white" when both surfaces are reflecting light from a common broad-band source (e.g., the sun). This notion has been formalized through the construct of the "optimal color" which refers to theoretical maximum reflectance (relative to "white") that can be achieved for a given chromaticity (or "hue/saturation value" on the 1931 CIE chromaticity diagram). The relationship between the maximum theoretically achievable luminance (relative to "white") as a function of chromaticity was quantitatively modeled by MacAdam (1935) and has since been known as the *MacAdam limit* in the color science literature. Reference to **Figure 3** shows that surfaces colors in the "yellow" area of the CIE chromaticity diagram can achieve MacAdam limits approaching 80-95 percent of reference white while those in the "red" and "blue" regions attain MacAdam limits as low as 10-20 percent of the reference white level.



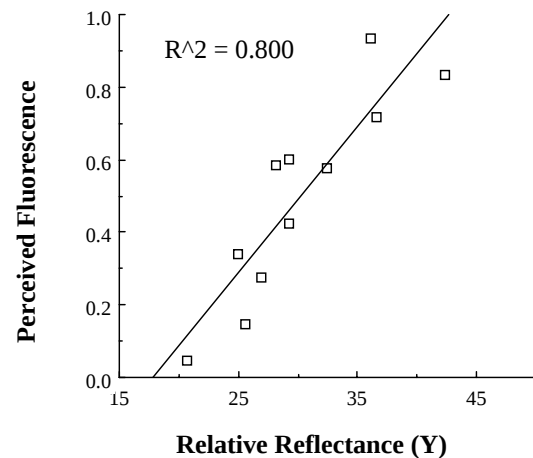
Evaluating the MacAdam Limit Normalization Model

Combining the findings of Evans and the speculation of Schultze, it can be argued that a necessary condition for the perception of fluorence may be the visual system's computation of a surface reflectance value that exceeds some internal representation of the maximum value attainable given its chromaticity (x,y); that is, a violation of some function of the MacAdam limit. The visual system's ability to establish such an internal representation is supported by the work of Bonato and Gilchrist (1994) who demonstrated evidence for an internal representation of the "white level", even in the absence of a white stimulus exemplar. Surface colors exceeding this limit (which must be "fluorescent" by definition) would appear to be fluorent. This mechanism can be extended such that the magnitude of the fluorescent sensation would then be related to some variant of the MacAdam Limit normalization function expressed in Equation 1.

As mentioned above, Schultze (1953) provided no experimental data to test the MacAdam limit noralization model of the appearance of fluorescent colored stimuli. In an attempt to provide such a test, the current investigator

searched the scientific literature and other sources for existing data sets relating the luminance of fluorescent colored materials to psychological judgments of their apparent luminosity or fluorence. Two such data sets were identified and analyzed:

Thielert and Schliemann (1972) used the *Method of Paired Comparisons* (i.e., Thurstonian scaling) to generate a psychological scale for the apparent luminosity of fluorescent colored paper samples varying in Y (relative reflectance) across restricted regions of CIE chromaticity space. Their data relating scaled psychological ratings of apparent luminosity to the stimulus parameter Y are plotted in **Figure 4a**. Inspection of the plot reveals that simple linear regression of Y accounts for approximately 80 percent of the variance in the proxy measure for the appear-ance of fluorence (i.e., $R^2=0.80$). There is a strong relationship between appearance and luminance as would be expected. **Figure 4b** shows the same data after applying the MacAdam limit normalization function. Note that scaling the stimulus luminance value with the MacAdam limit at each stimulus chromaticity resulted in a regression function that accounted for nearly all of the remaining variance in the appearance data (i.e., $R^2=0.96$). These findings give strong



support to Schultze's (1953) elegant and original proposition.

Figure 4a. Perceived fluorence as a function of stimulus relative reflectance (Data from Thielert & Schliemann)

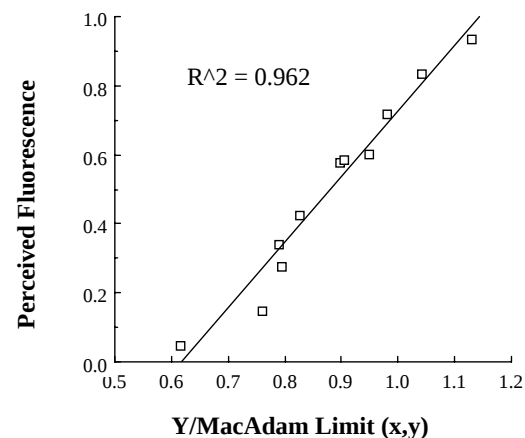


Figure 4b. Perceived fluorence as a function of the MacAdam limit normalization of stimulus relative luminance (Data from Thielert & Schliemann)

Analyses performed on a second data set also supported the application of the MacAdam limit normalization function for modeling the suprathreshold appearance of fluorescent colors varying in relative luminance. Dennis Couzin of the Avery Corporation reported the results of a study via a *Technical Memorandum to the ASTM Subcommittee on Fluorescence - E12.05* (undated). A magnitude estimation technique was used to obtain subjective ratings of the "amount of fluorescence" perceived for an assortment of red-to-orange stimuli varying in luminance (reported in CIE Y units). Regression analyses revealed that variations in the relative luminance accounted for only 25 percent of the variation in the subjective ratings of the degree of

fluorence ($R^2 = 0.249$). A somewhat better fit probably would have been obtained if the individual data had been aggregated using the *geometric* rather than arithmetic mean (Stevens, 1975). However, applying the MacAdam limit normal-ization demonstrated that a regression on **Y/YMacAdam(x,y)** accounted for nearly 83 percent of the variation in the rated subjective experience of fluorence ($R^2 = 0.825$).

Conclusions

Analyses of archival data generated support for Schultze's (1953) elegant but long ignored psychophysical model for the appearance of fluorescent colored materials. These findings have powerful implications for the specification and future investigation of a wide range of materials used in safety and warning applications. Finally, a psychological mechanism approximating an internal representation of the MacAdam limit may also have broad explanatory power when considered within the context of Evans' fluorescent threshold data (as a function of stimulus wavelength) and related color appearance phenomena such as the *Helmholtz-Kohlrausch effect* (i.e., heterochromatic brightness matching results).

References

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for providing translation services.

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Note 1

An English language translation of Schultze (1953) is available upon request. Special thanks to the *3M Company*