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Chromatic Callier Effect and its Repercussions on the Digitization of Early Film Colors

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Abstract. *The projection on screen has always been the supreme result of cinematography. Thus the digitization of a motion picture should seek to recreate the visual impression in the cinema. The image-forming particles contained in early color films can generate remarkable differences between a film directly observed with diffuse backlighting and its image projected on screen. In the recent decades this discrepancy has been largely overlooked by the film preservation community (film curators, scanner manufacturers, colorists, etc.). This paper re-establishes the importance of referring to the visual impression in the cinema, and describes the spectral variation of the Callier effect that can significantly alter early film colors when digitized. We have introduced the term "chromatic Callier effect" and described its repercussions on film digitization reporting case studies of tinted and toned film prints. The experimental results highlight that important changes are required in the optical design of film scanners to improve the digitization of motion pictures.* © *2019 Society for Imaging Science and Technology.*
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1. INTRODUCTION

Cinema theaters around the globe have almost completely converted to digital projection, and mechanical film projectors are only used by a restricted circle of film enthusiasts. At the time of writing of this paper, a few LED cinema screens have been installed [1], suggesting that the cinema of the future might use emitting screens without projection. Regardless of whether the projection booths will actually be dismantled, access to the content of film reels relies largely on their digitization, which is supposed to deliver a digital visualization that matches the cinematographic images as seen in analog cinemas. The degree of success of this match depends on the digitization itself (i.e. image capture, processing and data storage) and the visualization of the digital data. The video player, digital display device and viewing conditions are crucial for the result of the visualization. These latter components will be discussed only in passing here, image capturing and processing being our main focus.

The main stages for the digitization of a motion picture are image capture with a film scanner and color correction at a color grading suite. Professional color grading suites are powerful workstations where colorists can place their expertise and creativity at the service of new film productions. Film digitization, on the other hand, does not require creativity, as the objective of the digitization is to recreate the appearance of the analog film. The "faithful appearance" of a motion picture, to be conserved and transmitted to the future, must be identified by reflecting on the concepts of the artwork's *integrity* and *authenticity* [2]. When talking about a painting, the appearance of the work of art is defined by its unique material basis. By contrast, an analog film is not only a material object; it is ultimately performed as an ephemeral audiovisual *event* in cinema theaters by means of projection. With a few exceptions, such as home movies, film production used to involve the creation of several film elements (camera negatives, inter-negatives, answer prints, exhibition prints, etc.) for each cinematic work. Unlike negatives or rush prints, projection prints contain the transformations introduced by color grading and are therefore a better reference for the recreation of the hypothetical original appearance on screen. Their colors today, however, may have been corrupted by fading and other kinds of decay. In addition, even when conservation conditions are good, we must consider that the different copies that were sent to the cinemas often did not look identical even at the date of their creation.

For many movies the surviving material elements are fragmentary and a complete element may not be available, so it becomes necessary to assemble the digital version by joining together scans from different source materials. The colors of each of these parts must be graded in a different way in an effort to give a consistent "look" to the movie across its full length.

In view of all this, the color correction of a digitized film is not only a matter of color science and digital color management, but also requires curatorial judgments from film scholars and archivists whose trained eye and research into historical sources provide them with a basis to determine a look that is historically and esthetically justified.

This foreword seeks to briefly make the reader aware of the wide range of complexities arising in the digitization of the cinematographic heritage. The remainder of this paper will focus on questions that pertain to imaging and color science, describing certain case studies of projection prints that are in good conservation condition, such that the determination of the appearance of the films in question can be addressed as a largely technological problem. As will be explained in more detail below, however, this task cannot be

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undertaken with a colorimetric characterization of the film scanner.

2. FILM SCANNERS AND COLOR RENDITION

The quality of the data produced by a film scanner is determined by several factors connected to the optical and mechanical operating systems, the electronic components, and the image processing protocols. Here the attention is focused on two factors having fundamental influence on color rendition.

2.1 *Spectral Bands: Color Separation versus Color Accuracy*

The spectral bands of a film scanner are mainly determined either by the emissions of a composite light source (e.g. red, green and blue LEDs) and/or by some filtering system (e.g. Color Filter Array). The former approach is preferable, as it provides the possibility to independently adjust the intensities of the light components, making the best use of the sensor's dynamic range for all degrees of dye fading and all types of *colored couplers* [3] (the so-called "orange mask" of chromogenic negatives).

All professional film scanners available on the market to date use three spectral bands to acquire colors. Several scanner manufacturers opt for narrow spectral bands that do not overlap, considerably deviating from the average human's chromatic response (Figure 1). These spectral bands exclude those regions where typical dyes of recent films do not exhibit their absorption peaks and their absorbances largely overlap. When scanning subtractive three-color films, such choice reduces the dyes' *cross-talk* and increases "color separation" (a term often used by scanner manufacturers to indicate this feature of their products). Color separation has important benefits when scanning color negatives, and it can greatly improve the digital restoration of faded film colors. However, the selectivity of this spectral arrangement can represent a severe limiting factor for color rendition, especially when scanning early film colors. For example, *Pontacyl Brilliant Blue A* ("Cine Blue Green") is a dye that was commonly used to tint film during early cinema [4]. It exhibits strong absorption around 620 nm, which is responsible for its blue-green color. A film scanner with the spectral bands reported in Fig. 1 (they do not cover the regions below 430 nm, around 490 nm, and between 550 and 650 nm) misses the absorption of this blue-green dye, so its color cannot be detected.

Ideally, a film scanner should be able to adjust its spectral bands according to the type of film to be scanned. For instance, this could be achieved with additional spectral bands that would be included when it becomes necessary to compensate for the gaps left by the three spectral bands conceived for color separation.

2.2 *Light's Directional Arrangement: Film Projection versus Film Scanning*

The spectral bands of a film scanner have a fundamental role in color rendition, but there is another aspect, often

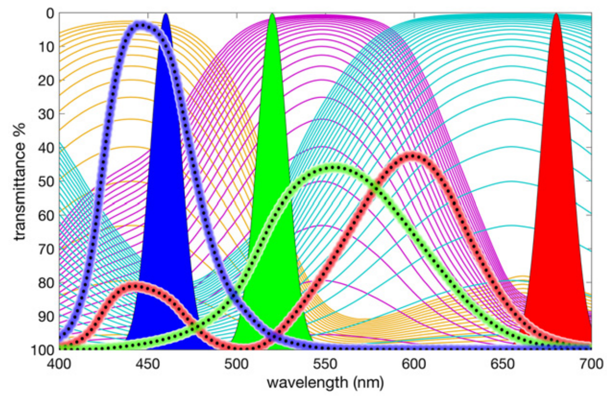


Figure 1. Typical transmittances of yellow, magenta and cyan dyes of "modern" film (solid curves). Narrow spectral bands that maximize color separation (blue, green and red areas) and CIE color-matching functions (dotted curves) are overlaid.

neglected, that can have a strong influence on how film colors are seen and digitized: the direction of the light rays illuminating the film.

Film projection in cinema theaters requires an extreme image magnification. The luminous flux on the big screen has to be sufficient to guarantee sufficient image brightness. To increase the luminous flux, the light source (ideally a *point source*) of traditional film projectors is located in the focus of a parabolic mirror, which directs the light toward a condenser. The condenser consists of a set of lenses that focus the light further and direct it to the main lens assembly, which images the photographic emulsion on the reflecting cinema screen. Beginning in the 1940s [5], *fly-eye lenses* were included in the condensing system to improve brightness homogeneity on the screen and reduce *vignetting*. "Condensed illumination" is the term that will be used here to indicate the manner in which a film is illuminated in a projector (Figure 2A).

All of the most popular film scanners available on the market to date create digital files of cinematographic images illuminating the film with a light diffuser (e.g. opal glass or integrating sphere), which provides a *diffuse illumination* (Fig. 2B). This type of illumination has the important advantage of attenuating the dark marks of dust and scratches on the film. (In recent years a scanner was available with an optical setup that combined diffuse and condensed illuminations [6]. This illumination system, however, was not conceived to prevent the color discrepancies shown in Fig. 2, but rather to emphasize and detect dust and scratches for their digital restoration [7].)

The condensed illumination of film projectors and the diffuse illumination of film scanners are opposing types of the directional arrangement of light. In perfect condensed illumination each point of the film receives light from one direction only, while in diffuse illumination each point of the film receives light from all directions. Some film types illuminated in these two opposing manners create quite different images (e.g. Figs. 2C and 2D). The present

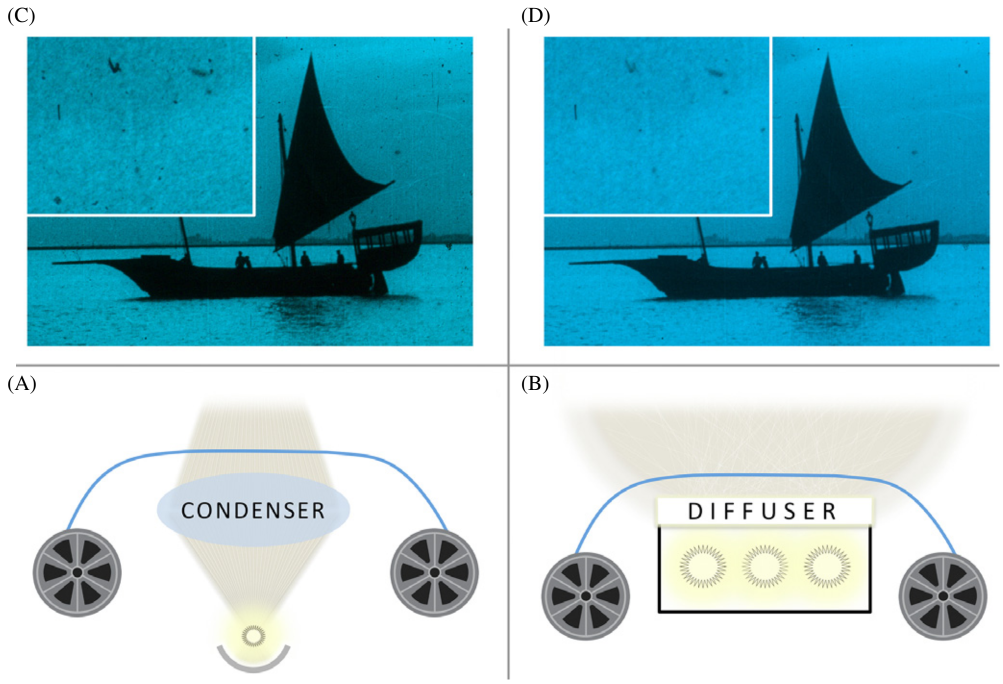


Figure 2. Below: Schemes of condensed (A) and diffuse (B) illuminations. Above: Color images of a blue tinted film frame captured in the two different illumination types (C and D, respectively). An image detail is magnified on the top-left part.

paper investigates these differences, focusing attention on the discrepancies in color.

3. EARLY FILM COLORS

The introduction of color in cinema is a complicated story that began at the turn of the twentieth century. The first decades of color cinema were characterized by a multitude of methods [8]: tinting and toning, hand coloring techniques, additive screen processes, two-color subtractive processes, spatial and temporal syntheses, and other methods. In the course of cinema's technical evolution the vast majority of these methods were abandoned, and a few efficacious processes emerged and were progressively improved. By the 1940s, film colors were generally and increasingly created with three-color subtractive processes.

There is a distinctive optical characteristic in the vast majority of processes that were in use during the first decades of color cinema: the presence of scattering particles (in most cases metallic silver) that play a fundamental role in the discrepancies between the images created in diffuse and condensed illumination. The scattering particles disappeared in modern color film. The three-color subtractive processes of modern cinematography (such as the films marketed as *Technicolor*, *Eastmancolor* and *Kodachrome*) produce images that are constituted by three layers of dyed gelatin emulsion. The silver halides continue to be responsible for the dye formation, but in most cases the metallic silver is not part of the final image at the end of the processing (except for *bleach bypass* prints or Technicolor prints that contain a *key image*). The resulting gelatin/dye system has a rather homogeneous refractive index (meaning the real part of the refractive index, if its complex notation is considered); therefore the film scarcely scatters light. The incident light is either absorbed or *specularly* transmitted (i.e. without scattering). By contrast, the gelatin-embedded inorganic particles that constitute the images in early color films cause significant light scattering. This is the case for additive screen processes [9], such as Autochrome and Dufaycolor, applied colors, such as hand and stencil coloring, and tinted and toned films. These optical characteristics can be responsible for some disappointment when seeing colors in projection. The problem was known in the early period of filmmaking, as documented in a passage from a 1920 course book [10]:

> "Many practical methods have been worked out from time to time for the toning of lantern slides and photographic papers. When these are applied to the toning of motion picture film, the toned film obtained in most cases, although apparently satisfactory when viewed in the hand, appears substantially black on projection. Generally speaking, the color of the image as seen in the hand is no criterion whatever of its appearance on the screen, so that in judging any particular tone it is essential to view the projected image."

4. COLOR CORRECTION OF FILM SCANS

In view of the complexities described in the Introduction, the color correction of the digital files created by a film scanner is not a straightforward task. Moreover, as we have already pointed out, if the light's directional arrangement and its consequences on the film appearance are not properly considered, early film colors are at risk of being significantly altered through their digitization. As long as film scanners use diffuse illumination, even the most rigorously executed *color management* practices [11] designed in an effort to minimize *metamer mismatch* [12] cannot fix the color discrepancies such as those shown in Fig. 2.

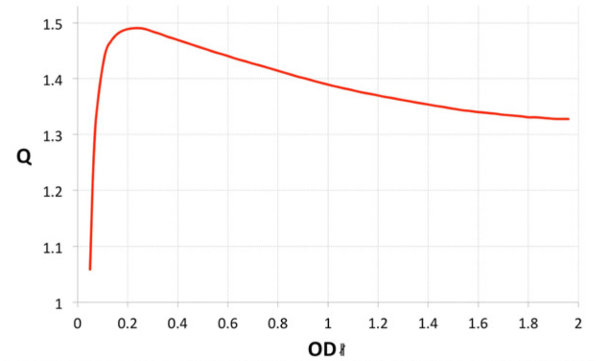
The projected image of a film print that still carries original unfaded colors is the proper reference for the color correction of its scan. A simultaneous display of the digital image and the image created by a mechanical film projector (ideally contemporary with the film production) on the screen can offer the proper comparison to seek a visual match in color grading. Full control on the color-managed pipeline of the digital workstation is necessary. Moreover, the simultaneous display must be arranged in a way that the digital and analog images have the same viewing angle and the same brightness, and are displayed on backgrounds with the same brightness and chromaticity; this arrangement allows bypassing most of the problems related to color appearance phenomena due to mismatched viewing conditions [13].

Unfortunately, it must be considered that most mechanical projectors do not allow stopping on a frame, proceeding at lower speed, or rewinding, such that the procedure described for color correction can become quite challenging. In addition, early color cinema was mostly shot on cellulose nitrate film, the projection of which is today prohibited in many countries (unless restrictive instructions are followed [14]). For these reasons, it is common practice to backlight the film with a light box (diffuse illumination) and use it as a reference for color correction. Due to the mismatched illumination type, this approach unfortunately may result in a digital version that deviates significantly from the appearance of the projected film.

5. THE CALLIER EFFECT AND RELATED SCIENTIFIC LITERATURE

The directional arrangement of the light rays illuminating a silver-based photographic film and the amount of scattered light that is collected by an imaging/viewing system (i.e. its *angular aperture*) have a strong influence on sharpness and contrast of the image created by the film. This has been known for many years, for example through observations of the differences between the paper prints created by condenser and diffuser enlargers, the difference between the image directly seen on a backlit film and its projection on screen, and the relatively low contrast of contact prints, whose equivalent angular aperture is 180°.

All these phenomena can be ascribed to the *Callier effect*, named after the scientist who defined the Q factor, i.e. the ratio between the optical density of a photographic film measured in specular configuration ($OD_{\parallel}$) and the corresponding optical density measured in diffuse configuration ($OD_{\nparallel}$) [15]. Callier concluded that there is a range of densities where Q can be approximated to a constant. After Callier's pioneering study, further experiments were published by Tuttle [16], who also confirmed a linear relation



$OD_{\nparallel}$	0.0	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
$OD_{\parallel}$	0.0	0.30	0.59	0.86	1.13	1.39	1.64	1.90	2.14	2.4	2.65

Figure 3. Above: Typical trend of the Q factor as a function of the diffuse density, as reported in [17] for a silver-based film. Below: Corresponding values of diffuse and specular density.

between $OD_{\parallel}$ and $OD_{\nparallel}$. Streiffert [17] put together a measuring apparatus that allowed describing the phenomenon in better detail. Figure 3 reports a typical curve obtained by plotting the Q factor as a function of $OD_{\nparallel}$. Q is always greater than one. It is close to one for low densities, it increases very rapidly, then starts diminishing slowly after reaching its maximum. In all plots reported in Streiffert's work [17] Q reaches its maximum value well below $OD_{\nparallel} = 1$.

With the use of filters and phototubes, Streiffert [17] also analyzed the relation between the Q factor and the wavelength of light, concluding that "Q is lowest for infrared light and increases as the wavelength is reduced, until the highest value is reached with ultraviolet light. This is, as would be expected, because of the known fact that the light-scattering property of an emulsion increases with decreasing wavelength of the light." The study also confirmed that a dye-based film which does not significantly scatter light produces a negligible Callier effect, so the Q factor is approximately one in the whole range of densities.

The visual result of the Callier effect is reported in the discrepancy between the images 2-C and 2-D of a film tinted with *Aniline blue R* [18]. Condensed illumination creates an image of the tinted film that has deeper darks and crisper grain; dust grains and scratches are also accentuated. On the other hand, diffuse illumination creates an image with lower contrast, softer film grain and attenuated dust particles. Not only do images 2-C and 2-D differ in sharpness and contrast, they also differ in color, owing to the wavelength-dependent scattering phenomena behind the Callier effect [17, 19]. Since the Callier effect is stronger for short wavelengths, the tinted film shown in Fig. 2 has a more pronounced blue component in diffuse illumination, whereas it appears greener in condensed illumination.

6. "CHROMATIC" CALLIER EFFECT

The present section reports on our investigation of the relationship between the Callier effect and the wavelength of

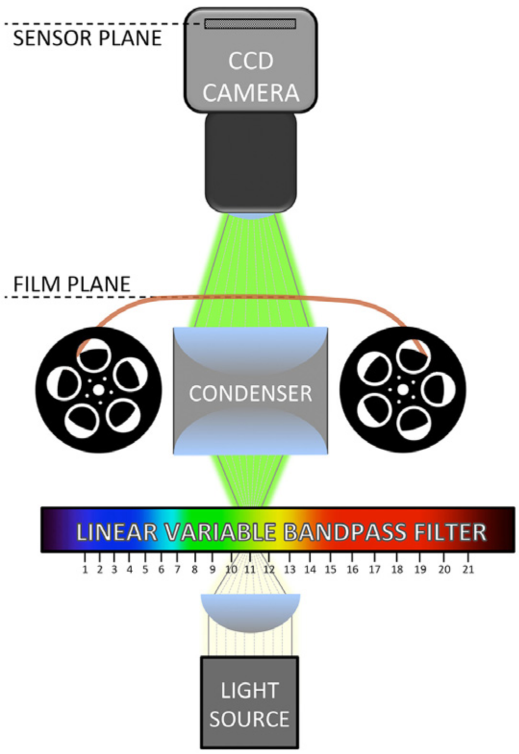


Figure 4. The measuring setup adopted for the acquisition of the multispectral images in condensed illumination.

light, plotting the Q factor for a set of spectral bands in the visible range (*chromatic Callier effect* or *spectral Q factor*).

6.1 *Multispectral Imaging System*

The measuring setup used for this purpose is a custom-made multispectral imaging (MSI) system working in transmission geometry, which provides a condensed illumination to the film. The scheme of the system is reported in Figure 4. A linear variable interference band-pass filter selects spectral bands from the collimated emission of a *Light Emitting Plasma* bulb. Two aspheric lenses (condenser) focus the spectrally selected diverging beam at the principal plane of the camera objective. The camera employs a 65 mm f/2.8 macro-lens (*f-number* was set to 8 and never changed) and a 16-megapixel full-frame monochrome CCD with a nominal dynamic range of 67 dB. By opportunely positioning the band-pass filter, 21 equally spaced spectral bands with a FWHM of around 18 nm were set between 400 and 720 nm. For each spectral band, the *integration time* was determined by the highest signal in the scene, which was set around one-eighth below the saturation level, thus covering the full range of voltages where the linearity of the sensor is guaranteed to 3%. Three images were acquired with the determined integration time: the image of the film frame (*film*), the image without film (*white*) and the image without light (*dark*). To increase the signal-to-noise ratio, all images were obtained by averaging 10 captures. The band at 400 nm (where the sensitivity starts dropping toward the UV) required the highest integration time, thus having the

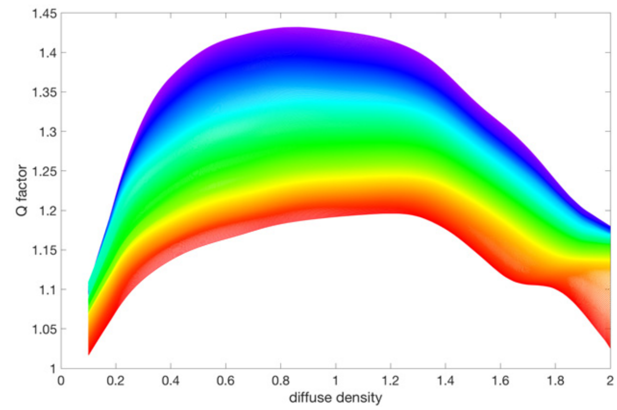


Figure 5. Spectral dependency of the Callier *Q*-factor plotted between 400 and 720 nm with an intuitive "rainbow" color code.

highest *dark current*. A cooling system based on circulating liquid counteracted the heating of the camera, thus reducing the dark current. All camera elements and the film were not moved during the image acquisition of the same frame, so all images were perfectly registered. Film transmittances (T) were calculated through standard *flat-fielding correction*: $T = (film - dark)/(white - dark)$.

The interposition of an opal glass between the condenser and the film (Fig. 4) allowed for switching easily from condensed to diffuse illumination.

6.2 *Experimental Measurements*

The spectral trend of the Q factor was measured for a black-and-white film. A specific frame was chosen for its well-distributed range of optical densities, from the brightest point devoid of silver particles ($OD_{\#} \approx 0.1$) to the darkest point ($OD_{\#} > 2$). Two multispectral transmittance images were collected (cf. Section 6.1), one in condensed and another one in diffuse illumination. The optical densities are given by the equation $OD = \log_{10}(1/T)$, and these were used to plot a Q factor curve. A *pchip* interpolation was applied on the spectral and diffuse density dimensions, resulting in the plot shown in Figure 5.

The measurements used to draw the plot in Fig. 3 [17] were carried out with the same illumination geometry (specular) while changing the collection geometry. By contrast, our measurements (Fig. 5) were carried out with the same collection geometry (*angular aperture* ≈3°, i.e. specular) while changing the illumination geometry. If the *Helmholtz reciprocity principle* holds true, these two different approaches can be considered equivalent.

7. PREDICTING THE COLOR IN CONDENSED ILLUMINATION

The curves shown in Fig. 5 refer to the specific silver-based film chosen for the measurement. Nevertheless, it was interesting to assess to what extent these curves can be used to predict the optical densities of other silver-based films in condensed illumination from their corresponding diffuse optical densities. This could provide a numerical model to

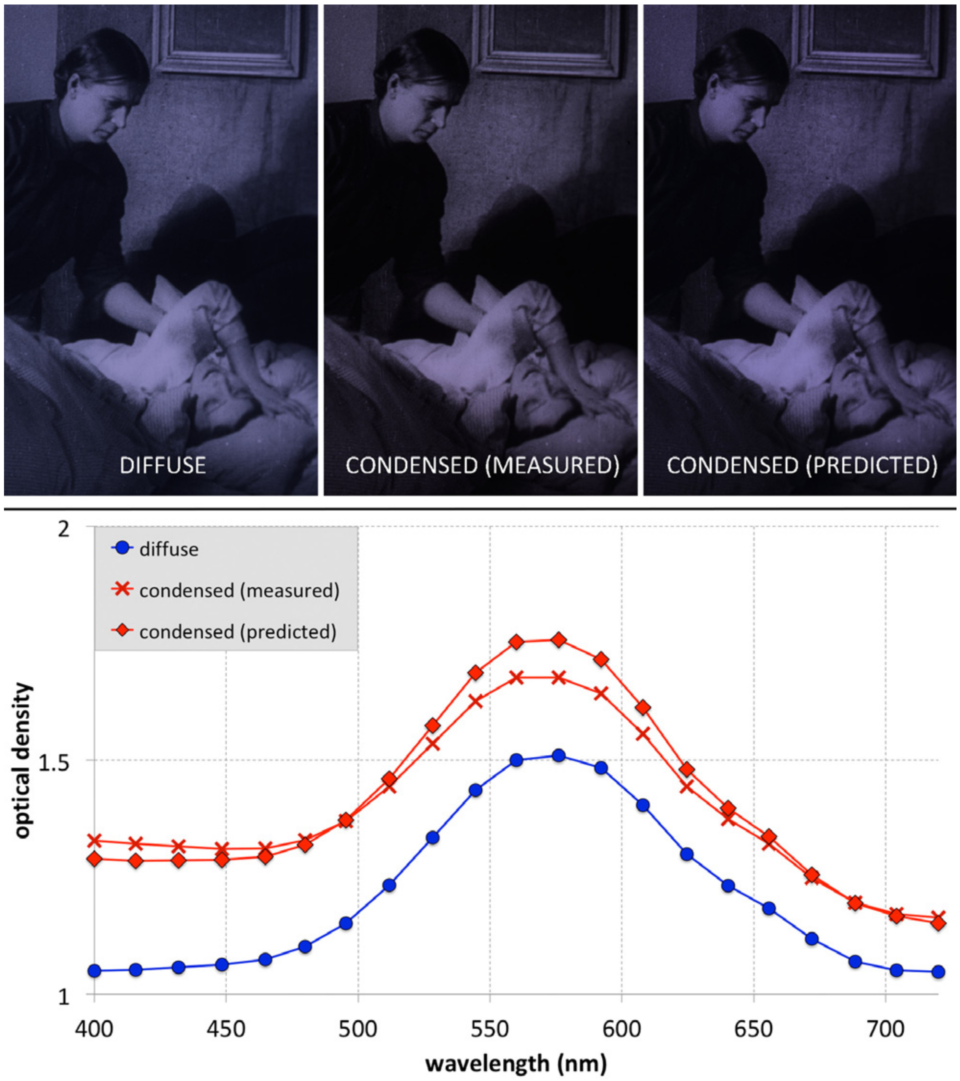


Figure 6. Predicting the optical densities of a tinted film in condensed illumination. Above: Color images calculated from the multispectral images. Below: Average spectral density of the images.

confront the condensed/diffuse color discrepancies that, as discussed in Sections 2.2 and 3, may significantly alter the results of film digitization.

A tinted film is a positive black-and-white print that has been immersed into a dye bath. The dye homogeneously attaches over the entire photographic emulsion, conferring a uniform coloration to the whole image. After tinting, the emulsion consists of black silver particles immersed in a colored gelatin. A violet-tinted sample was selected for the experiment. Two multispectral images of the selected sample were captured with the system described in Section 6.1, one image in condensed and another one in diffuse illumination. The corresponding optical densities are indicated here with $OD_{\parallel}^{\mathrm{film}}$ and $OD_{\nparallel}^{\mathrm{film}}$, respectively.

7.1 *Computing the Optical Density in Condensed Illumination*

It is assumed that for both illumination conditions the optical densities of the tinted film are the sum of two addends:

- OD^{Ag}—the optical density of the silver image, and
- OD^{dye}—the optical density of the dye.

The above assumption is the base of the "Desmet" preservation methods [4]. The silver image is subjected to the Callier effect, so $OD_{\parallel}^{\mathrm{Ag}} = OD_{\nparallel}^{\mathrm{Ag}} \times Q$. The dye itself does not scatter light (i.e. no Callier effect) and its concentration is considered constant across the image. Therefore, OD^{dye} can be obtained in any illumination condition from the brightest parts of the image, which do not contain silver particles. Given these assumptions, the optical densities of the film in condensed illumination were derived by the following equation:

$$OD_{\parallel}^{*\,\mathrm{film}} = [(OD_{\nparallel}^{\mathrm{film}} - OD^{\mathrm{dye}}) \times Q] + OD^{\mathrm{dye}}. \qquad (1)$$

The result of the prediction is reported in Figure 6 for a portion of the film. The plot contains the spectral densities calculated from the average transmittances measured in diffuse (circles) and condensed illumination (crosses). The curve marked with diamonds represents the result of the prediction with (1).

7.2 *Colorimetric Calculations*

Color images can be computed from a film's transmission spectra in different ways depending on scope. The digitization of a motion picture has as its ultimate goal the match between the visual stimuli created by the original screening equipment and the new visual stimuli created with digital screening equipment. Assuming the same conditions of observation for the digital and analog screenings (i.e. the conditions found in cinema theaters), basic colorimetry is enough to achieve this goal, albeit observer metamerism is a limitation [20]. In practice, the visual stimuli are presented in the complicated spatiotemporal arrangement of pictures in motion, and their appearance is likely to deviate from the color in *aperture mode* considered by basic colorimetry [21]. At the same time, however, this complicated arrangement occurs in the digital screening in the same way it occurred in the analog one, so the color appearance phenomena have the same effect and can be disregarded in the color calculations.

The color images shown in Fig. 6 are the result calculations performed on the three multispectral images ($OD_{\parallel}^{\text{film}}$, $OD_{\nparallel}^{\text{film}}$ and $OD_{\parallel}^{*\,\text{film}}$). The constituting steps of these calculations are described here. The optical densities were first converted to transmittances. Tristimulus values were calculated using the standard integrations [22] with the CIE 1931 2° color-matching functions [23] and the standard illuminant *D50* [24]. *DCI-P3* was chosen as destination color space [25], since it is commonly used in video and motion picture productions, and it contains all colors of the film samples used in the present paper (no *gamut mapping* was necessary). A 3-by-3 matrix represents the linear transformation between two vector spaces: the tristimulus space *XYZ* and the *linear RGB* space. The matrix was calculated from the tristimulus values of the space's primaries and white-point adapted to the D50 with the Bradford Chromatic Adaptation Transform [26]. The resulting matrix for *DCI-P3* is the following:

$$\begin{bmatrix} R^{lin} \\ G^{lin} \\ B^{lin} \end{bmatrix} = \begin{bmatrix} 2.5999 & -1.1611 & -0.4185 \\ -0.8353 & 1.7883 & 0.0204 \\ 0.0492 & -0.0997 & 1.2755 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}.$$

Finally the gamma (2.6 for *DCI-P3*) is encoded and a TIFF-16 bit file is saved. A detail of the three resulting images is shown at the top of Fig. 6.

7.3 *Evaluation of Results*

As expected, the image acquired in condensed illumination (central image) has deeper darks than the image acquired in diffuse illumination (left image). Additionally, a color difference is notable, with the image in condensed illumination being "more reddish" and the image in diffuse illumination being "more bluish." This color difference is in agreement with the previous findings on the chromatic Callier effect (Section 6), indicating that the blue component (short wavelengths of light) is attenuated more strongly in the image captured in condensed illumination.

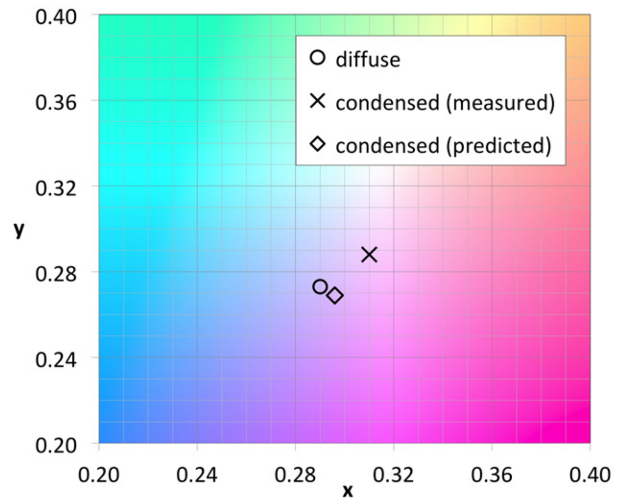


Figure 7. The result of the color prediction in condensed illumination for a tinted film plotted in CIE chromaticity diagram. The more closer the diamond is to the cross (than the circle), the better the color prediction.

The three curves reported in Fig. 6 show that the optical densities predicted by (1) are close to the "real" measured spectra. However, the visual result is not prodigious: Eq. (1) correctly enhanced the image contrast, but the outputted predicted color (right image) is only slightly closer to the measured color (central image) than the input color (left image). The poor result in terms of color is numerically expressed by the corresponding chromaticity values reported in Figure 7: $x = 0.290$, $y = 0.273$ for the image captured in diffuse illumination, $x = 0.310$, $y = 0.288$ for the condensed illumination image, and $x = 0.296$, $y = 0.269$ for the predicted image. The predicted color (diamond) is only slightly closer to the target color (cross) than the original color (circle).

8. AUTOMATIC COLOR CORRECTION

Section 4 described a possible approach to correct the colors of a digitized projection print film. The correction is achieved operating on the panel of a color grading suite, seeking a visual match between the digital output and a reference image created with an analog apparatus. A digital match of the cinematographic image can be computed from the multispectral image captured in condensed illumination (see Section 6.1 for technical details) doing the color calculations with the spectral emission of a light source used by mechanical film projectors contemporary with the production of the film in question (e.g. *carbon arc*). The resulted digital image is a more valid reference for the digital color correction of a tinted and toned film than, for instance, the film stock itself as seen on a light box [10].

The flowchart shown in Figure 8 (to be read following the blue, green, yellow and red arrows in succession) describes the color correction procedure, which consists of the following steps:

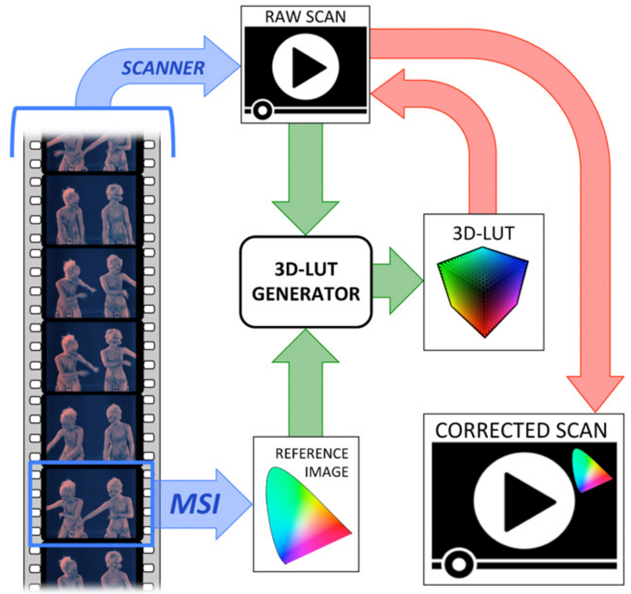


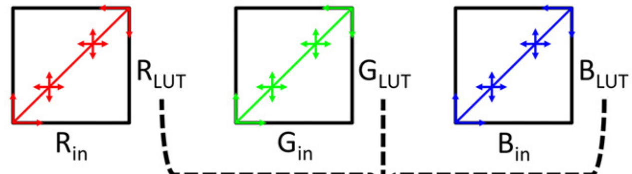
Figure 8. Flowchart describing the automatic color correction of film scans (follow blue, green and red arrows in succession).

- All film frames are digitized with a conventional film scanner and one representative frame is acquired with the MSI system.
- The color image calculated from the multispectral acquisition (*reference image*) and its corresponding image from the *raw scan* are compared by a computer routine (*3D-LUT generator*) to find the transformation that minimizes their difference in color.
- The resulting transformation, formatted as 3D-LUT [27], is applied to the raw scan to correct its colors.

The actual validity of the 3D-LUT for the whole film (or for a section of it) requires that the scanning parameters remain unchanged during the scan, i.e. all film frames are captured with the same light intensity and spectral distribution, and with the same integration time and aperture. In addition, the representative frame used as color reference has to contain the range of colors that the 3D-LUT is supposed to correct; film frames with colors that deviate from the color content of the reference image are likely to be handled poorly by the 3D-LUT. Thus, whenever the color composition of the film changes and the reference image does not contain the new colors, a new 3D-LUT must be created with a new reference image.

8.1 *3D-LUT Generator*

The main part of the color correction process is the "3D-LUT generator" routine (Fig. 8) that takes two RGB images of the same film frame as input and outputs a 3D-LUT that minimizes their color difference. The RGB images come from two different imaging devices, so a prior *feature-based image registration* [28] is necessary for the pixel-to-pixel comparison (as chosen by [29]). The 3D-LUT does not need to perform any creative grading. It in fact performs



$$\begin{bmatrix} M_{RR} & M_{RG} & M_{RB} \\ M_{GR} & M_{GG} & M_{GR} \\ M_{BR} & M_{BR} & M_{BB} \end{bmatrix} \begin{bmatrix} R_{LUT} \\ G_{LUT} \\ B_{LUT} \end{bmatrix} = \begin{bmatrix} R_{OUT} \\ G_{OUT} \\ B_{OUT} \end{bmatrix}$$

Figure 9. Constituent structures of the 3D-LUT: (above) three 1D-LUT defined by white value, black value and two midpoints, plus (below) a 3-by-3 matrix (M). The input values (R_{in}, G_{in} and B_{in}) are first processed by the 1D-LUTs, and then multiplied by the matrix.

a "digital calibration" of the film scanner with the current parameters. It is therefore sufficient to process the raw scan with just four simple *structures*: three 1D-LUTs (one for each color channel) and a 3-by-3 matrix that adjusts color saturation (see Figure 9). Each 1D-LUT is a curve defined by its black value (one variable), its white value (one variable) and two midpoints that can move up/down and left/right (two variables each). The total number of variables is eighteen for the 1D-LUTs, plus nine for the matrix. The routine finds the optimal values for the twenty-seven variables though a multistep minimization process based on the *Nelder–Mead simplex algorithm* [30]. The resulting four structures are "enclosed" in a 33^3 sized 3D-LUT and saved as a *.cube* file [27]. All professional color grading applications recognize this file format and can easily apply the 3D-LUT to the film scan.

9. AUTOMATIC COLOR CORRECTION OF A TINTED AND TONED FILM

Metallic toning is a coloring technique that transforms the silver image in a metal-salt compound. After toning the emulsion consists of colored image particles immersed in gelatin. The compound substituting the metallic silver can be *iron ferrocyanide* for blue, *copper ferrocyanide* for red/brown, *silver sulfide* for sepia or *uranium ferrocyanide* for reddish brown [4]. A toned film is colorless in the bright parts of the image, while the shadows and the dark parts are colored in the specific hue. Tinting (Section 7) can be combined with toning to obtain composite effects.

A tinted and toned print film was selected for testing the automatic color correction described in Section 8. The nitrate silent film is of unknown origin and belongs to the collection of the *Deutsches Filminstitut* in Frankfurt (*DIF 50 123*—"Tänze"—1920). It is a compilation of dance numbers, divided into sections in different settings, each having its own color composition. One of these sections combines a deep blue toning and a pink tinting. A frame was captured with the MSI system in condensed and diffuse illuminations. During the early period of cinema carbon arc lamps were in use, so *blackbody radiation* at 5380 K ($x = 0.335$, $y = 0.344$) was

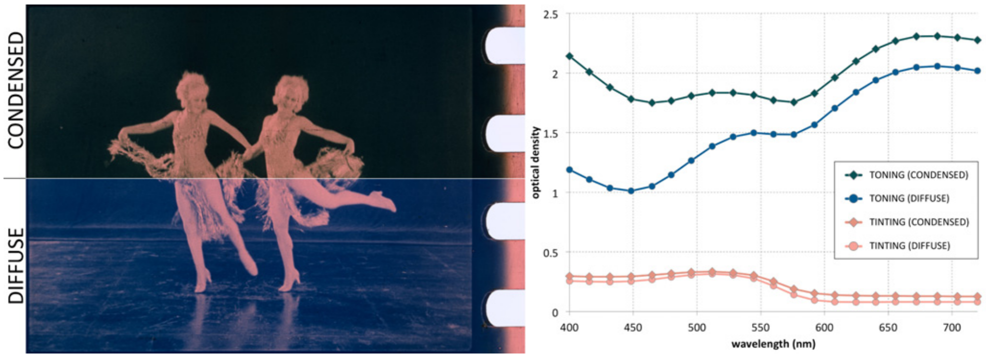


Figure 10. Multispectral acquisition of a tinted and toned film (DIF 50 123—"Tänze"—1920). Left: Color images in condensed (upper half-image) and diffuse illumination (lower half-image). Right: Spectral densities of selected areas.

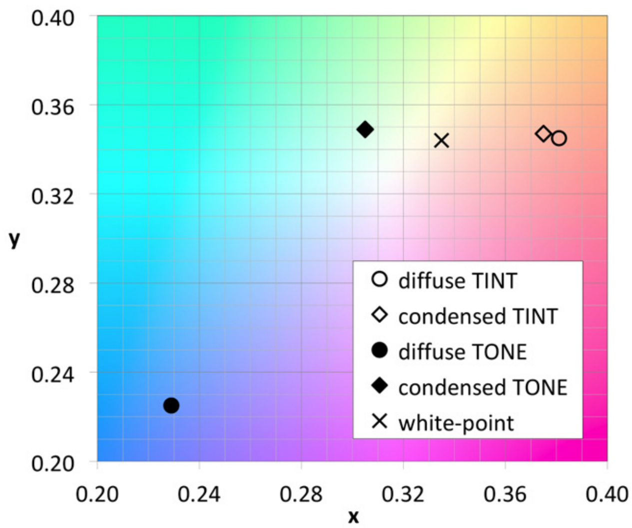


Figure 11. Tinting and toning colors of "Tänze" plotted in the CIE chromaticity diagram. The toning color is completely different when changing between condensed and diffuse illumination, while the tinting color remains substantially the same.

used for the calculations, as it approximates the emission of the *Suprex* type carbon arc [31]. The resulting color images (cf. Section 7.2) are shown in Figure 10. For the two kinds of illumination, Fig. 10 also reports the spectra of two regions corresponding to the dark-toned background and a pink area between the perforation holes. The brightest parts of the image contain the pink tinting dye and few or no toned particles, so light scattering is only due to dirt and scratches. The color of these parts appears a little darker in condensed illumination, exhibiting a very small change in chromaticity (see the points plotted in CIE chromaticity diagram, Figure 11). By contrast, the color of the dark background, which is constituted by highly scattering particles, exhibits an extreme color change from a deep blue in diffuse illumination ($x = 0.229$, $y = 0.225$) to a dark green in condensed illuminations ($x = 0.305$, $y = 0.349$). This very diverse color shift between the dancers and their background radically alters the chromatic balance of the image (see Fig. 10).

The four-minute film was digitized with a scanner that illuminates the film diffusely and a minimally processed video file (raw scan) was saved. The automatic color correction (cf. Section 8) of the blue/pink section of the raw scan was performed by reference to the condensed and diffuse images. Even though the image in condensed illumination is the suitable reference to recreate the hypothetical cinema projection, it was interesting to test the 3D-LUT generator with both reference images and then calculate the residual color difference in the two cases. Figure 12 shows the residual colorimetric difference as Euclidean distance in the CIELAB space [32] calculated pixel by pixel on registered and downsampled images. The ΔE is considerably higher when the image in condensed illumination is used as the reference (upper half of Fig. 12) than when the diffuse illumination image is used instead (lower half of Fig. 12). In the case of diffuse reference, the scanner and the multispectral system illuminate the film with the same directional arrangement, so the color correction routine can easily find a transformation that provides a good visual match both for the toned dark areas and the tinted highlights. In the case of condensed reference, on the other hand, the mismatching directional arrangements of light rays between the two imaging systems require a complex processing that operates differently on the dark areas and on the highlights. The four simple structures used by the 3D-LUT generator (Section 8.1) cannot compose a transformation that simultaneously and successfully adjusts the clear pink highlights and the highly scattering dark areas.

10. CONCLUSION

This paper has introduced the concept of the "chromatic Callier effect" and described its implications for the scanning of early color films. The examples reported show that colors risk alteration through digitization because film scanners use diffuse light. This problem can be confronted either by designing a scanner that illuminates the film with condensed light or by relying on image processing.

The chromatic Callier effect depends on the characteristics of the silver particles making up the photographic image [17]. This has been confirmed by the experiment reported in Section 7, which showed that the spectral Q factor

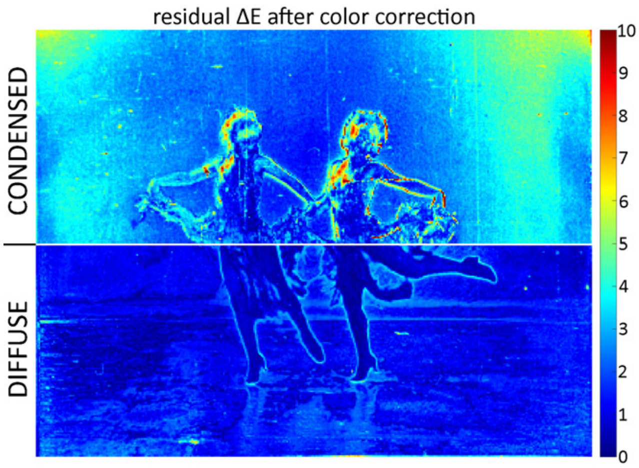


Figure 12. Residual colorimetric distance after automatic color correction of "Tänze" using the condensed (upper half) and diffuse (lower half) reference images.

of a specific silver-based film does not necessarily fit another silver-based film. Therefore, depending on the film tinted, the same tinting dye is likely to deliver different colors when projected. It follows that it is not possible to find a generic correction method based on image processing that accurately predicts the color of a film in condensed illumination from its color in diffuse illumination.

The projected color of a toned film can be remarkably different than the color directly seen with diffuse backlighting [10]. As presented in Fig. 10, the chromatic balance of a tinted and toned film when inspected on the bench can significantly deviate from the projected image of the film. The experiment reported in Section 9 indicates that recreating the color balance in projection from a digital scan in diffuse illumination would likely require a cumbersome procedure of image segmentation and local processing.

These results suggest that the faithful color appearance of early film colors can be reproduced with digital means only if the scanning is performed by illuminating the film with condensed light. In addition, as briefly discussed in Section 2.1, the spectral bands of film scanners should be designed to take into consideration non-standard film dyes, as were commonly used during the early period of color cinema. The foregoing aspects should be guiding principles for the design of a new generation of film scanners.

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