Conflicting Colors: Film Scanning versus Film Projection

Giorgio Trumpy; University of Zurich; Zurich, Switzerland
Rudolf Gschwind; University of Basel; Basel, Switzerland

Abstract

The directional arrangement of the illumination plays an important role on image contrast and sharpness of silver-based photographic film. This paper explores how the directional arrangement of light (directed or diffuse) affects cinematographic colors. The experimental results show that a consistent color difference can be observed between the image projected on screen (directed illumination) and the image acquired with a scanner (diffuse illumination), no matter how well the scanner is calibrated. This fact has to be properly considered in film scanning and color correction; otherwise early color films can be notably distorted during the digitization process.

Introduction

For many decades the public exhibition of motion pictures took place exclusively in cinema theaters. Projection on cinema screens has always been the supreme display of film productions, even when 'home cinema' became the most common modality of film consumption.

The extreme image magnification of movie projection requires a very high luminous flux on the screen. To increase the luminous flux, in traditional film projectors the light source is located in the focus of a parabolic mirror, which directs the light towards the 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. *Directed illumination* is the term that will be used here to describe how a film is illuminated in a projector (Fig. 1-a).

To date, almost all cinema theaters around the globe have converted to digital projection, and traditional film projectors are only used by a restricted circle of film enthusiasts. Therefore, the easy access to the content of film reels relies only on their digital replica, which is supposed to create a digital visualization that matches the cinematographic images created by 'old-style' film projectors [1].

The vast majority of film scanners create digital replicas of cinematographic images illuminating the film with a light diffuser (e.g. opal glass, or integrating sphere), which provides a *diffuse illumination* (Fig. 1-b). This type of illumination has the advantage of easily obtaining a uniform illumination across the film gate, and reduces the appearances of blemishes, such as dust and scratches.

The directed illumination of film projectors and, on the other hand, the diffuse illumination of film scanners are exact opposites as for the arrangement of ray directions. In directed illumination each point of the film receives light from only one direction, while in diffuse illumination each point of the film receives light from all directions. Some film types illuminated in these two opposite manners create quite different images (e.g. Fig. 1-c and 1-d), and this difference can lead to digital replicas with bad color reproduction.

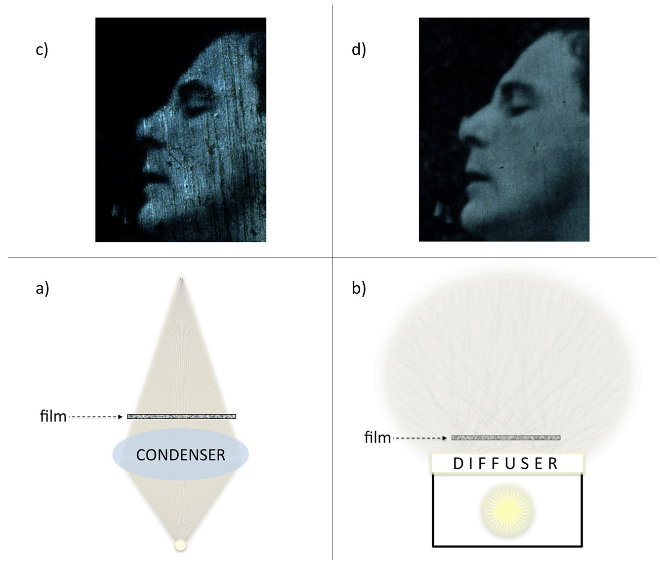

Figure 1. Below: Schemes of directed (a) and diffuse (b) illuminations. Above: Corresponding images of a photographic film (c and d respectively). The film is a print of "Das Cabinet des Dr. Caligari" (R. Wiene, 1920) that underwent metallic toning.

This paper highlights the importance of the type of illumination in film digitization, exploring how the directional arrangement of light affects cinematographic colors, providing a contribution to the development of new approaches for the digitization and restoration of film colors.

Scientific background

The directional arrangement of the rays illuminating a silver-based photographic image plays a fundamental role in its sharpness and contrast [2]. Figure 1 depicts the two different types of illumination at the bottom, and shows the corresponding acquired images at the top. The illustration 1-a depicts the setup in which the film is illuminated by means of a condenser, which provides aligned light rays (directed illumination). Contrarily, in illustration 1-b the film is illuminated by means of a diffuser, which provides scattered light rays (diffuse illumination). The resulting images of a metal-based photographic film adopting the two types of illumination have different sharpness and contrast. In directed illumination the image (Fig. 1-c) is much 'crisper' and scratches are emphasized; in diffuse illumination the image (Fig. 1-d) appears 'softer', with smoothed details and lower contrast.

This discrepancy has been known over a long period of time in black-and-white still-photography, observing the differences between the prints created with condenser or diffuser enlargers. The phenomenon became known as '*Callier effect*', named after the scientist who defined the Q-factor, i.e. the ratio between the

optical densities of a photographic film measured in directed and diffuse illuminations [3].
The Callier effect is determined by the scattering phenomena at the silver particles, which are known to be wavelength-dependent [4]. As a consequence, the images created with directed and diffused illuminations not only differ in sharpness and contrast, but they also have different colors (as the images in Fig. 1). To date, no study has been published on the spectral dependence of the Callier effect (probably due to the fact that this color shift has no influence in the printing of black-and-white photographs). The present work fills this gap by investigating experimentally the relation between the Q-factor and the wavelength of light.
The results of this study are particularly interesting for several types of early color films. The images on "modern" color film (i.e. chromogenic monopack) are constituted of dyes that scarcely scatter light; therefore these images do not significantly change with the type of illumination. On the other hand, in case of photographic color images comprised of scattering particles (usually metallic silver) [5], for instance additive screen processes, such as Autochrome and Dufaycolor, or applied colors, such as hand and stencil coloring, as well as tinted and toned films, light is intensely scattered and a strong Callier effect is produced. If this phenomenon is not properly considered, the appearance of applied colors, which were used in early cinema for metaphorical associations and to articulate the narrative structure, risks to be altered significantly by the digitization. In fact, the different illumination manner determines an intrinsic color mismatch, which is not related to the capability of the film scanner to accurately measure colors.

Measuring setup

The experimental method used here was to acquire two multispectral transmittance images of a photographic film using directed and diffuse illuminations.
The measuring setup is depicted in Figure 2. The light was provided by a plasma lamp, coupled with a liquid light guide and a collimating adapter, generating a parallel broadband light beam. An aspheric condenser lens focused the light into a linear variable interference band-pass filter, where the center wavelength of the passed band shifts linearly across its length. Two other aspheric lenses focused the spectrally selected diverging beam coming out of the filter (FWHM = 20 nm) at the principal plane of the camera objective. The imaging system consisted of a 65 mm f/2.8 macro lens and a 16 Megapixel full-frame CCD monochrome camera. Each multispectral image was created combining 31 images between 400 and 700 nm, with a spectral step of 10 nm. The calculation of film transmittances was done with a flat-field correction, referring to the blank images without film and dark images.
A light diffuser could be inserted just before the film to be imaged (see Fig. 2), switching from directed to diffuse illumination.

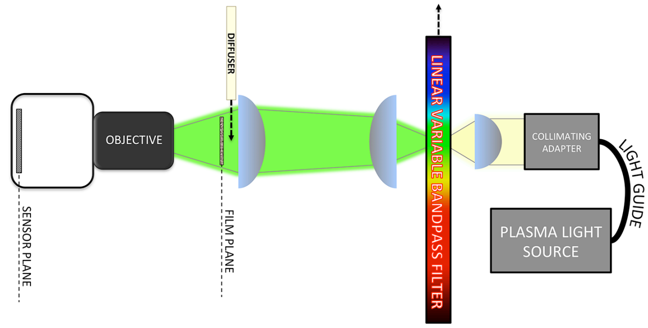

Figure 2. The measuring setup adopted for the acquisition of the multispectral images

Spectral dependence of the Q-factor

The Q-factor (Q) is the curve obtained by plotting the ratio between the optical densities of a photographic film measured in directed ($OD_{\parallel}$) and diffuse ($OD_{\nparallel}$) illuminations as a function of $OD_{\nparallel}$.

$$Q = OD_{\parallel} / OD_{\nparallel} \quad \textit{(as a function of } OD_{\nparallel}\textit{)} \tag{1}$$

For a silver-based film (high scattering) Q is always found to be equal to or greater than unity [2], while for dye-based film (low scattering) Q is close to 1 and the Callier effect is negligible.
A black-and-white silver-based film was selected for the measurement of the spectral dependence of the Q-factor. A specific frame was selected for its well-distributed range of optical densities, from the brightest point (devoid of silver particles) to the darkest point ($OD_{\nparallel} \simeq 2.2$). Two multispectral images were collected in directed and diffuse illuminations with the experimental setup described in the previous section. A Q-factor curve was built for every spectral band. By imposing the point [0, 1] (a completely transparent point does not scatter light, so Q is by definition equal to 1), and applying interpolation processes on the spectral- and density- dimensions, Q has been determined for all $OD_{\nparallel}$ in the range [0, 2.4] and all wavelengths in the nanometer range [400, 700]. The resulting plot is reported in Figure 3.

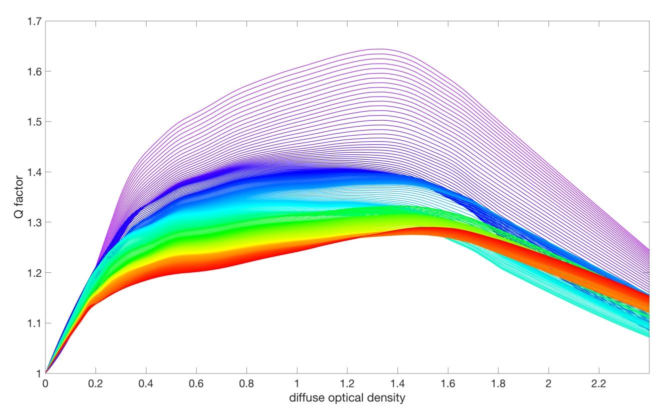

Figure 3. Spectral-dependency of the Callier Q-factor plotted between 400 and 700 nm with an intuitive "rainbow" color code.

The case of a tinted film

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.
It was interesting to evaluate how well a model based on the data reported in the plot of Figure 3 is able to predict for a tinted film the optical densities in directed illumination from the optical densities measured in diffuse illumination.
A blue-green tinted sample was selected for the experiment. Two multispectral images were acquired from the selected sample, one in directed illumination (setup depicted in Fig. 2 without diffuser), and a second in diffuse illumination (with diffuser). The two multispectral transmittance images were converted in optical densities (indicated as $OD_{\parallel}^{film}$ and $OD_{\nparallel}^{film}$ respectively).

A simple model is to consider that, in both illumination conditions, the optical densities of the tinted film is the sum of two addends:

1. OD^{Ag} - The optical density of the silver black-and-white image, which is subjected to the Callier effect (eq. 1), so $OD_{\parallel}^{Ag} = OD_{\nparallel}^{Ag} \times Q$, and
2. OD^{dye} - The optical density of the green dye, which is constant across the image and independent of the type of illumination (as non scattering). So $OD_{\nparallel}^{Ag} = OD_{\nparallel}^{film} - OD^{dye}$.

Given these assumptions, and combining the corresponding equations, the optical densities of the film in directed illumination are derived by the following equation:

$$OD^*{}_{\parallel}^{film} = [(OD_{\nparallel}^{film} - OD^{dye}) \times Q] + OD^{dye} \quad (2)$$

where OD^{dye} is given by the optical density measured in diffuse illumination in correspondence to the brightest point of the tinted film where no silver is present ($OD_{\nparallel}^{Ag} = 0$).

Colorimetric calculations were carried out on the three multispectral images ($OD_{\parallel}^{film}$, $OD_{\nparallel}^{film}$ and $OD^*{}_{\parallel}^{film}$)[1] to obtain the CIE XYZ tristimulus values, using the standard illuminant D50 and the CIE 1931 2° Standard Observer, and then converted in RGB image files [6, 7]. A detail of the three resulting images is reported in Figure 4. A plot with the average absorption spectra calculated over the whole image is also reported in Figure 4.
As expected, the image acquired in directed illumination (central image) looks sharper and has higher contrast than the image acquired in diffuse illumination (left image). Moreover, dust grains and scratches are more visible in directed illumination. In addition to this, the color difference is visually notable, with the image in directed illumination being 'more green' and the image in diffuse illumination being 'more cyan'. The average chromaticity values calculated over the whole image (from spectra in Figure 4) are x=0.275, y=0.375 for the directed illumination, and x=0.250, y=0.352 for the diffuse illumination.
This color difference is explained by the spectra reported in the plot of Figure 4 that indicates that the short wavelengths are significantly less absorbed in diffuse illumination.

[1] The asterisk indicates the optical densities that are not measured, but rather calculated from the model.

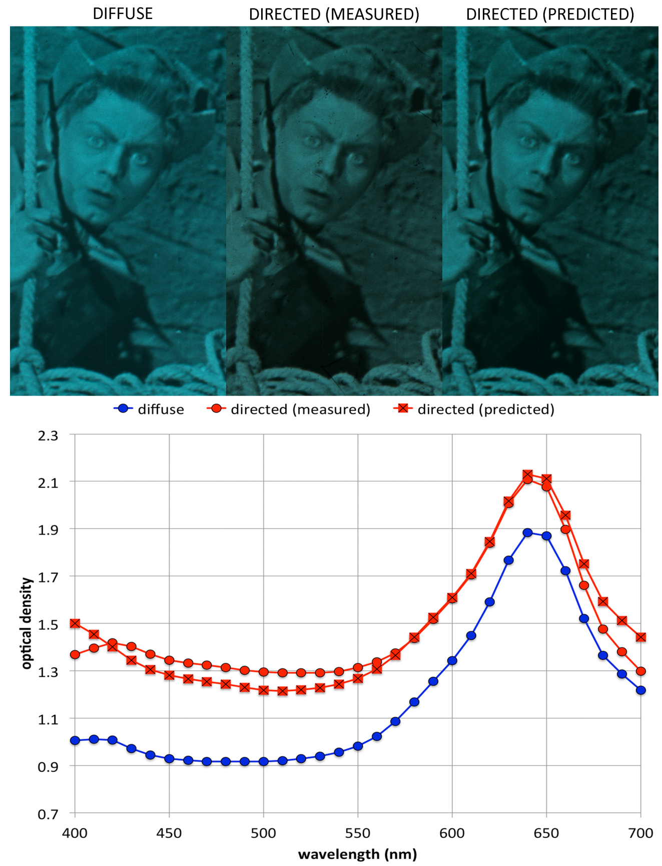

Figure 4. Above: Color images calculated from the multispectral images (details). Below: Average absorbance spectra calculated over the whole multispectral image.

The third curve in the plot is the average spectrum of the predicted optical densities $OD^*{}_{\parallel}^{film}$, which moves close to the "real" measured spectrum, albeit without coinciding with it.
The visual outcome is displayed with the third image detail (right image), whose colors move close to the measured colors (central image), albeit without reaching them. The average chromaticity of the predicted image is x=0.261, y=0.372.

Further experiment on toned film

Film toning is another film coloring technique; it involves a chemical reaction that transforms the silver image and replaces it with a colored metal-salt compound. After toning the emulsion consists of colored image particles immersed in a colorless gelatin. The compound substituting the metallic silver can be iron ferrocyanide (Prussian Blue) for blue, copper ferrocyanide for red/brown, silver sulfide for sepia or uranium ferrocyanide for reddish brown [5]. 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 and toning can be combined to obtain composite effects. An example of this combination is reported in Figure 5. The film, which is toned in deep blue and tinted in pink, was imaged in directed and diffuse illuminations with the setup depicted in Fig. 2. The resulting images reported in Figure 5 exhibit very different colors in the two types of illumination.

The unexposed part to the left of the perforation (tinting dye only) does not have scattering image particles; hence the color only slightly changes. The color of the dark background remarkably changes, with chromaticity values varying from x=0.199, y=0.201 in diffuse illumination to x=0.259, y=0.331 in directed illuminations, resulting in a significant reduction of color saturation.
The mid-tones are accordingly affected.

Figure 5. Tinted and toned nitrate positive print (DIF 50 123 - "Tänze") from the collection of Deutsches Filminstitut - DIF, Frankfurt. Color image calculated from the multispectral acquisition in diffuse (upper half-image) and directed illumination (lower half-image).

Conclusions

The experiments presented in this paper demonstrate that the type of illumination plays a fundamental role in the colors of a metal-based photographic film.
The Callier effect is definitely stronger for short wavelengths (Fig. 3). For all wavelengths the maximum Callier effect is between 1.3 and 1.5 $OD_{\nparallel}$. The crossings of the curves reported in Figure 3 suggest the concurrence of multiple phenomena.
The physical model expressed by Equation 2 was used to predict the appearance of a tinted film in directed illumination from the multispectral image acquisition in diffuse illumination. The computed image get close to the appearance of the film in directed illumination (Fig. 4), meaning that the model is satisfactorily able to describe the optical phenomena occurring on a tinted film. The residual discrepancies can be ascribed to different characteristics of the silver particles of the sample that has been used to define the model (a non-colored film) and those of the sample that has been used to test the model (a tinted film).
The measurements carried out on a tinted and toned film (Fig. 5) demonstrate that the color mismatch between the images obtained with the different types of illumination can be significant in case of toning.
In conclusion, the film colors in directed illumination (typical of film projectors) and the colors of the same film in diffuse illumination (typical of film scanners) may differ strongly. This effect has to be taken into account, especially when embarking in the scan of early film colors, such as additive screen processes and applied colors.
Further studies will assess the feasibility of creating effective 3D lookup tables that correct the colors of digital scans carried out with diffuse illumination. These 3D-LUTs will also have to consider the particular spectral emissions of old cinema projectors.

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Authors Biography

Giorgio Trumpy studied Conservation Science in Florence, and received his PhD in Scientific Photography from the University of Basel (2013). His work has focused on Spectroscopy and Imaging Science for conservation of cultural heritage. For two years (2014-2016) was postdoc fellow at National Gallery of Art in Washington DC, designing spectral imaging methodologies for works of art. He is currently postdoc at the University of Zurich conducting scientific analysis of film color processes.

Rudolf Gschwind studied Chemistry at the University of Basel. During his studies he got involved with scientific photography. Since 1980 he was the Head of Department of the "Scientific Photography Lab" - University of Basel (now its name to "Digital Humanities Lab"). His main research topics are image processing and analysis, computational photography, color imaging, preservation of the audio-visual cultural heritage and digital archiving. He has been emeritus since 2014.