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Digital Unfading of Chromogenic Film Informed by Its Spectral Densities

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Abstract: A material-based approach for the digital restoration of chromogenic photographic and film materials affected by dye fading is proposed. Through a digital reconstruction of the original optical properties, the proposed restoration methodology approximates the original color appearance in a non-subjective manner, thus improving the results compared to conventional RGB tonal re-adjustment of the film scan both in terms of quality and presumed faithfulness to original appearance. In order to do so, the degree of fading is derived from neutral black parts of the film's image content, and the knowledge of the film material's spectral densities is used to digitally reconstruct the colors corresponding to the material's original dye concentrations and render them in an RGB space. For a comparison, results from conventional re-grading were adjusted to render them most similar—and thus comparable—to the results of the proposed spectrally informed digital unfading. The restored images obtained through spectrally informed unfading were deemed clearly superior in terms of color subtlety, color faithfulness and coherence.

Keywords: chromogenic film; dye fading; spectral densities; film scanning; digital restoration

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1. Introduction

A significant challenge in the preservation of color photographic and film heritage is the fading of the image dyes, which compromises the original appearance and commonly results in a pink/magenta cast deriving from the dominating residual dyes. Chemically, the breakage of intermolecular bonds in the dye molecules produces the fading [1], which visually manifests as the loss of contrast and reduction of the overall density of the image [2]. Moreover, as the stability characteristics of different dyes are usually not the same, the fading is uneven, resulting in color casts [3]. This irreversible form of deterioration is attributed to the instability of the image dyes used in photographic and cinematographic materials, particularly those produced between the 1940s and 1980s, and their susceptibility to storage conditions [4].

The gravity of this impermanence has been highlighted in audio–visual preservation communities since the 1970s [5,6]. Over the years, commercial photographic and film material manufacturers have endeavored to improve the stability of their color stocks [4,7]. Simultaneously, chemists, imaging and conservation scientists, in collaboration with the global archival community, have initiated multidisciplinary research focusing on the characteristics of chromogenic dyes, their subsequent aging [8–11] and possible measures for the preservation and restoration of affected photographic and film heritage [12].

Chemical restoration of dye fading is challenging as it involves targeting the physical locations of broken color dye molecule bonds [13]. However, digital restoration has been used alternatively to reconstruct the color appearance of historical photographic and film materials [9,11]. This process usually starts with a conventional RGB scan of the faded, historic materials and typically employs the available tools of color grading on the raw scans to adjust color balance and saturation [2]. In film production, color grading is deemed as a creative tool, empowering filmmakers to set the final aesthetics of the image to be screened. However, as a matter of fact, these color grading tools are also employed for the digital restoration of faded materials, using the same creative approach to compensate for changes in color balances and recover, as best as possible, the scene color and grading choices and ultimately a supposed original color.

In the absence of external color references (such as fragments of a non-faded positive print, input from the filmmakers, or, in the case of animation, original artworks), the determination of the supposed original color becomes a subjective process, drawing on factors such as memory color, knowledge of or assumptions about contemporary aesthetics, the presumed appearance of a color process at a given time in film history, artistic implications drawn from a filmmaker's oeuvre, or even less defined local preferences such as the "British Technicolor look".

Given the above limitations of a conventional digital restoration workflow, the capability of image processing to numerically reverse the fading and simulate the original color appearance in a more objective manner has been investigated over last decades [14]. However, the feasibility of an objective and accurate color reconstruction depends on the amount of residual color present in the film, the quality of the digital image capture and the efficacy of the image processing techniques. Our proposed methodology has taken into consideration the previous milestones in this area of research, some of which are highlighted subsequently. The definition of the contribution of the dyes' side absorptions in the digital image capture and development of the linear bleach model in the early 1990s [15,16] provided the crucial fundamental description, based on which digital restoration methods were developed as early as 1997, using correction matrices to account for the side absorptions [17]. In this case, the matrix coefficients were determined with a multitude of target reference colors. Furthermore, the possibility to remove the effect of side absorptions in the digitization process by testing the effectiveness of correction matrices based on both linear and offset bleach models were investigated over the following years [18].

Supported by a case study on faded chromogenic film samples, we propose a material-based spectral approach of digital restoration that achieves more convincing results from digital unfading by using the spectral densities of the image dyes in two stages: (I) to quantitatively determine the contribution of each emulsion layer (cyan, magenta, yellow) to the R, G and B digital image formation; and (II) to compute the supposed color aesthetics of the film material before fading.

2. Materials and Methods

2.1. The China Girls

For our case study, five sample frames of so-called China Girls were investigated (Figure 1a–e). China Girls were typically one-to-four-frames-long test images, mostly of female employees of the film laboratory or acquaintances of the laboratory workers [19], accompanied by color bars and gray patches. These fragments appeared in the countdown, i.e., before the beginning of the film, and were used to calibrate color timing or black and white density during the processing [20]. The etymological origin of the term China Girls remains debated, but is often attributed to the photographed models, which in some instances were mannequins made of porcelain, a material that is also referred to as "china" [21].

The investigated China Girls samples do not have adequate edge code inscriptions to derive details regarding the material's provenance, such as the year or country of manufacture [22]. However, consulting previous research and databases of the International Federation of Film Archives (FIAF) [23,24], supported by cultural–historical documentations about China Girls [25–27], and interpreting the annotations contained in the images of the sample frames, it was assumed that the selected samples were produced in the second half of 1970s using Eastman Kodak film materials. This time period represents a pivotal era between 1965 and 1985 when Kodak strived considerably to attain better stability of the image dyes used in chromogenic materials [7], which is exemplified through the introduction of 12 types of new negative films, 19 types of print films and 16 types of intermediate films during these two decades [28].

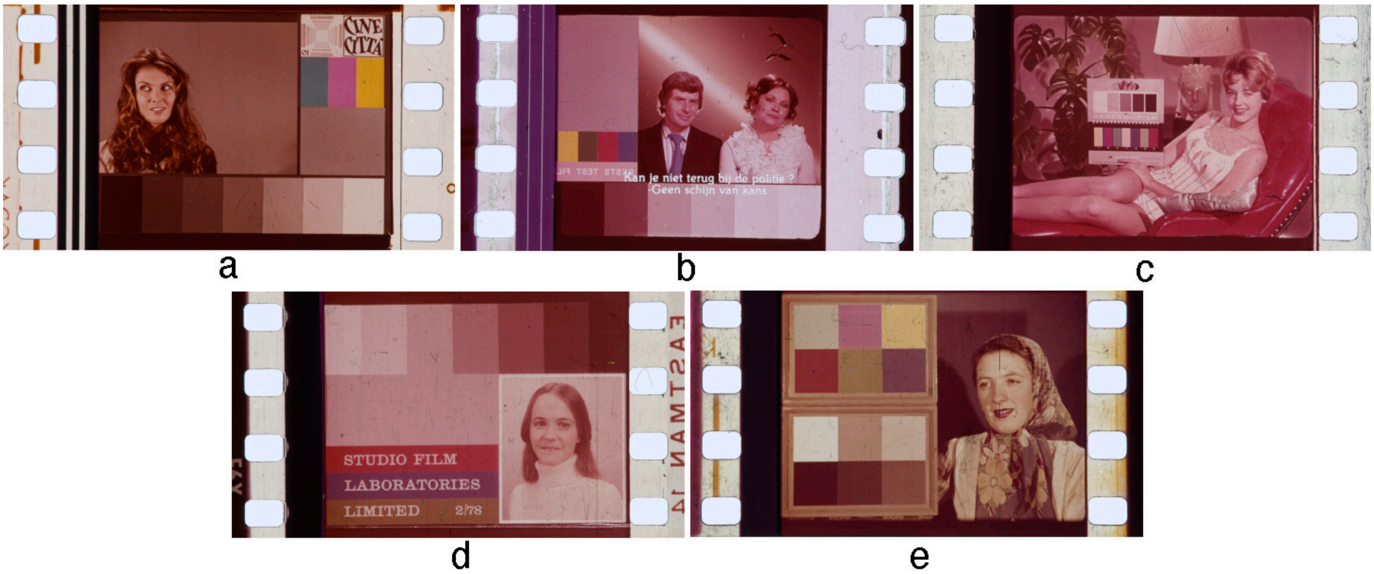

Figure 1. (**a**–**e**) The China Girl sample frames under study produced in the late 1970s on Eastman Kodak film stock.

Further bibliographical research aided the determination of the spectral characteristics of 35 mm positive and intermediate materials produced by Kodak during this period, such as Eastman Color Print Film 5381 [29], Eastman Ektachrome Video News Film (Daylight) 5239 [30], Eastman Ektachrome Video News Film (Tungsten) 5240 [31], Eastman High Contrast Positive Film 5362 [32] and Eastman Color SP Print Film 5383 [33] to name a few. As these film materials exhibit similar absorbance characteristics, we decided to process the five selected China Girls samples (Figure 1a–e) considering one single set of spectral densities: Eastman Ektachrome Video News Film (Tungsten) 5240 (abbreviated to Ektachrome VNF 5240), introduced in 1975 [34], was chosen for the processing.

2.2. Digital Restoration Method

To digitally restore the faded colors of chromogenic materials and reconstruct their supposed original appearance during film projection, our proposed material-based approach adopts principles of color science and image processing techniques, while being informed by historical research about the introduction and use of the film type under study and its technical characteristics. This method is based on two main assumptions about chromogenic film stock: (1) Considering that unlike silver-based black-and-white material, chromogenic, dye-based film is a non-scattering material; hence, the Beer–Lambert law is deemed to be valid; the overall spectral density of the film is the sum of the spectral densities of the individual dyes with weights corresponding to their local concentrations; (2) the fading of a dye can be modeled as a single multiplication factor that uniformly reduces the spectral densities of the individual emulsion layer containing the fugitive dye [16]. In view of the above assumptions, the absorption spectrum of a film at a certain position (x,y) is derived by the following equation:

$$ABS_{film}^{(x,y)}(\lambda) = ABS_s(\lambda) + \sum\nolimits_{i \equiv C,M,Y} \left(\frac{1}{F_i} \cdot k_i^{(x,y)} \cdot ABS_i(\lambda) \right). \tag{1}$$

The absorption spectrum of each emulsion layer is given by the product of $ABS_i(\lambda)$—indicating the dye's characteristic spectral density—the weight k_i—corresponding to the local dye concentration—and the inverse of the factor F_i—a value greater than 1 that expresses the degree of dye fading. The overall film absorption spectrum $ABS_{film}(\lambda)$ is the sum of the absorption spectra of the C, M and Y emulsion layers and that of the plastic support ABS_s, which can be discolored and are thus not perfectly transparent.

The proposed digital restoration method presented here is the extension of two already published works, the first of which laid the foundation of developing this approach [35] and the latter described the restoration of a faded Agfacolor chromogenic print from 1945 as case study substantiating the approach [36]. For our current case study of the five selected China Girls samples, the determination of the spectral densities of the samples (see Section 2.1) was essential to reconstruct, to the best of our knowledge, the original aesthetics of the faded film. The following subsections describe the steps of the proposed digital restoration method.

2.2.1. Step 1—Image Capture

The residual color information present in the samples was digitized with a multispectral imaging system with ten narrow bands in the visible range. The system is constituted by a 61-megapixel full-frame monochrome camera and a light source with 10 narrow-band LEDs. The spectral images are captured sequentially, and accurate transmittance values are obtained with a standard flat-field operation. Complete specifications and a thorough description of the image capture procedure can be found in a previous publication [37]. Transmittance multispectral images of the film samples were captured with 4430 ppi, allowing the recording of accurate colors in high level of detail to document the current material state (Figure 1a–e).

For the digital restoration procedure, however, only three bands were used out of the ten: the red, green and blue bands with sensitivity peaks at 672, 544 and 447 nm, respectively (Figure 2, top-left). These narrow RGB bands closely resemble the typical ones chosen by scanner manufacturers to minimize the "cross-talk" effect that is caused by the dyes' side absorptions, thus capturing images with enhanced color information [14,37].

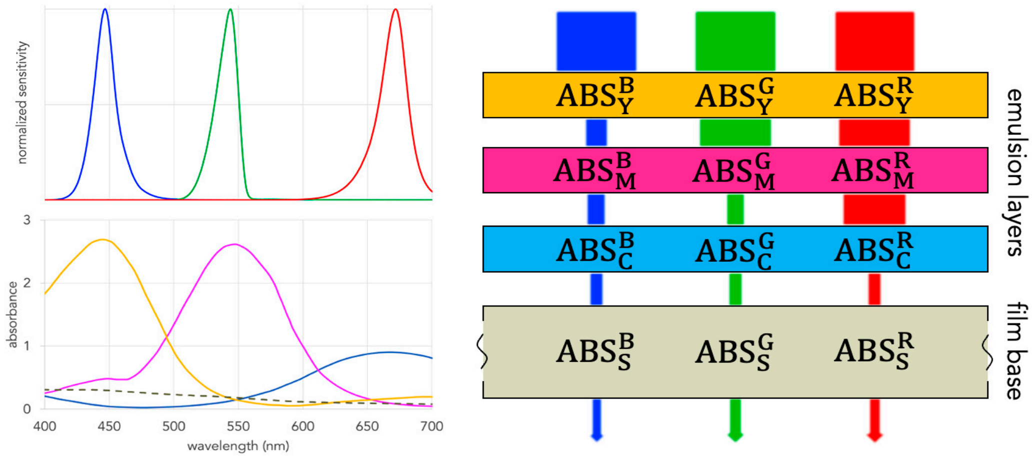

Figure 2. Left: Plots reporting the normalized sensitivities of the spectral bands (top) and the spectral densities of the film layers for an achromatic dark (bottom—emulsion layers in solid color lines and film base in dashed gray line). The reported spectral densities correspond to sample a. Right: Diagram illustrating the absorption events at each film layer for the blue, green and red spectral bands.

The digital restoration method that is presented here can be applied to films or photographs that have been already digitized; in such cases, one can commence from the following step.

2.2.2. Step 2—Determination of the Spectral Densities and their Fading

To implement the restoration method presented here, it is necessary to know the spectral densities of the film layers corresponding to a dark area (darkODs) that was supposedly achromatic in the original state, but it is now brownish due to fading, such as the unexposed part between the frames or the black patch of the grayscale chart present in the samples under study (Figure 1).

Measuring the absorbance spectrum of the individual dyes in a motion picture or photographic film is not a trivial task. In the present work, we decided to rely on the available technical documentation [29–33] to determine the analytical densities once the film is identified. To secure the future availability of such information, dedicated databases should be sustained [23,38,39].

To obtain the darkODs of the faded China Girls, the spectra of Ektachrome VNF 5240 were processed with fading factors (as expressed by Equation (1)), so the resulting integral film density (i.e., the sum of the densities of the four film layers—*C*, *M*, *Y* and base) corresponds to the color values of the black patch of the grayscale target for each sample. The absorbance of the film base was obtained considering the area between the perforation holes that is supposedly devoid of color dyes.

The samples present substantial fading of the yellow and cyan dyes, while the magenta dye is always well-preserved, corresponding to typical cases of chromogenic dye fading. The resulting dark spectral densities of sample a are reported at the bottom-left of Figure 2. In this case, the yellow and magenta dyes are well-preserved with absorption peaks above 2.5, while the cyan dye is considerably faded with the absorption peak below 1. The film base, the absorbance of which is indicated by the gray dashed line, exhibits a slight yellowing.

2.2.3. Step 3—Dyes and Film Base Contributions in the RGB Capture

The spectral approach for the digital unfading requires to numerically evaluate the contribution of all the film layers (emulsion dyes and base, the latter of which can generally be assumed transparent, but sometimes aging and degradation can compromise its transparency [7]) to the overall film absorption while the digital color image is captured. Two elements are necessary for this evaluation: (1) the spectral bands of the digital imaging system; and (2) the darkODs, i.e., the dark spectral densities described in Section 2.2.2.

The diagram on the right of Figure 2 depicts the absorption phenomena at the individual film layers: the blue light is mostly absorbed by the yellow layer, the green light by the magenta layer and the red light by the cyan layer. However, due to the dyes' side-absorptions and the imperfect transparency of the film base, there are minor but significant absorptions in all other layers. The twelve absorption phenomena are expressed by the following equation:

$$ABS_i^x = \int_{\lambda_{min}}^{\lambda_{max}} [darkOD_i(\lambda) \cdot band^x(\lambda)] / \int_{\lambda_{min}}^{\lambda_{max}} band^x(\lambda) \\ for\ x \equiv R, G, B\ and\ i \equiv C, M, Y, S \tag{2}$$

where $darkOD_i$ are the dark spectral densities, and $band^x$ are the spectral sensitivities of the digital imaging system. The interval of the integral $[\lambda_{min}\ \lambda_{max}]$ encompasses the visible range.

2.2.4. Step 4—Dye Purification

In view of the absorption phenomena described above, the captured images contain a mixed contribution of all three dyes in each color channel. In case of dye fading, some of these mixtures become less uneven, as the contribution of a faded dye in its corresponding digital channel (e.g., faded cyan in the red channel or faded yellow in the blue channel) becomes comparable with the contributions of the other dyes' side absorptions in the same channel. Thus, an image processing method is necessary to obtain images corresponding to the individual emulsion layers of the film, so a selective re-increase of the faded dyes' concentration can carry out a positive digital restoration of the film. This image processing method has been called "dye purification" [35].

The operations for the dye purification are executed after converting the R, G and B transmittance images into absorbance images and subtracting the slight absorption component of the film base: the resulting images correspond to the emulsion absorbance and are indicated by $Kimg^R_{dyes}$, $Kimg^G_{dyes}$ and $Kimg^B_{dyes}$.

To initiate the process, a fundamental approximation is considered: the image of the green band corresponds to the absorption of the magenta emulsion layer, so $Kimg^G_{dyes} \cong Kimg^G_M$. As a matter of fact, the yellow dye of chromogenic film stock generally has a low side absorption in the green band, and the cyan dye is generally the most faded; so ABS^G_Y and ABS^G_C are considerably smaller than ABS^G_M and they can be neglected (see Section 2.2.3 and Figure 2).

The dye purification unfolds in two stages: (I) the magenta side-absorption is subtracted from the blue band to obtain the yellow emulsion layer (the small side absorption of the faded cyan in the blue band can be fairly neglected); and (II) the magenta and yellow side-absorptions are subtracted from the red band to obtain the cyan emulsion layer. These two stages of the dye purification process are expressed by the following equations:

$$Kimg^B_Y = Kimg^B_{dyes} - \left[\left(ABS^B_M / ABS^G_M\right) \cdot Kimg^G_M\right] \tag{3}$$

$$Kimg^R_C = Kimg^R_{dyes} - \left[\left(ABS^R_M / ABS^G_M\right) \cdot Kimg^G_M\right] - \left[\left(ABS^R_Y / ABS^B_Y\right) \cdot Kimg^B_Y\right] \tag{4}$$

where ABS^x_i are calculated as expressed by Equation (2).

This is the suitable dye purification protocol for cyan fading. In the case of yellow fading, which was the type of fading affecting the Agfacolor print that has been restored as a part of the previous case study [36], the red capture is purified first to obtain the cyan layer and then the blue capture is purified to obtain the yellow layer.

The resulting images $Kimg^R_C$, $Kimg^G_M$ and $Kimg^B_Y$ represent the absorption phenomena of the single emulsion layers at specific spectral positions that are defined by the RGB sensitivities. Their values are proportional to the dye concentrations of the current faded state.

2.2.5. Step 5—Dyes Unfading

To restore the original colors of the China Girl samples (Figure 1a–e), the concentrations of the faded dyes (mostly yellow and cyan) have to be numerically increased to their supposedly original values. Once the images corresponding to the individual dye concentrations of the current faded state are calculated as described in Section 2.2.4, the original concentrations can be obtained with unfading factors. The unfading factors to be applied to $Kimg^R_C$, $Kimg^G_M$ and $Kimg^B_Y$ are determined considering the poorly exposed parts, which were supposedly achromatic dark before fading. The unfading factors are adjusted to obtain a low digital number for R, G and B in the final color image (resulting from step 7—Section 2.2.7), thus restoring the achromatic dark. As in Step 2, the black patch of the grayscale target in each sample was considered to perform the dyes' unfading.

2.2.6. Step 6—Spectral Reconstruction

In order to properly recreate the aesthetic of the unfaded film, it is necessary to associate the dyes' spectral densities to the restored concentrations. This is obtained with the new version of Equation (1) where the fading has been restored and the film base is considered perfectly transparent:

$$ODcube_{film}(\lambda) = \overline{Kimg}^R_C \cdot ABS_C(\lambda) + \overline{Kimg}^G_M \cdot ABS_M(\lambda) + \overline{Kimg}^B_Y \cdot ABS_Y(\lambda) \tag{5}$$

where $\overline{Kimg}^x_i$ are the restored dyes' concentrations, ABS_i are the spectral densities of Ektachrome VNF 5240 and $ODcube_{film}$ is the spectral cube representing the absorbance of the restored film. Following the recommendation of the Commission Internationale de l'Éclairage (CIE) for accurate color calculation [40], $ODcube_{film}$ contains absorbance values every 5 nm in the range between 380 and 780 nm.

2.2.7. Step 7—Color Calculation

By leveraging the psychophysical characteristics of the human visual system [41], the final aesthetic of the restored film is calculated from the spectral cube performing colorimetric calculations that consider the spectral emission of a Xenon arc bulb—commonly used in film projections since the 1950s—and the CIE 1931 2° Standard Observer [42]. For every pixel of the absorbance cube $ODcube_{film}$, the tristimulus values are obtained with the following summation:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \sum_{\lambda} Xe \cdot 10^{-ODcube_{film}} \cdot CMFs \tag{6}$$

where Xe is the spectral emission of the Xenon arc bulb and $CMFs$ are the color matching functions of the Standard Observer.

In order to obtain a conveniently readable image file, the resulting tristimulus values are scaled and converted to RGB values considering the DCI-P3 standard space [43].

3. Results

The results obtained with the proposed material-based, spectral approach of digital unfading are reported on the top row of Figure 3. In order to compare these results with a standard RGB method, the initial RGB images (Section 2.2.1) were processed with a specialized image-processing algorithm (LUTgenerator) [44], which was used to minimize the color difference with the result of the spectral approach. LUTgenerator finds the optimal values for three parametric curves through a multistep minimization process based on the Nelder–Mead simplex algorithm [45] and defines a simple one-dimensional look-up table [46]. The resulting images are reported on the bottom row of Figure 3. Their colors are the closest possible achievable with RGB curves to their above equivalent.

Figure 3. (**a**–**e**) Top: results obtained through the spectral approach of digital unfading. Bottom: results of a standard RGB tonal adjustment obtained with the "LUTgenerator" algorithm.

The comparison of the two image sets (Figure 3a–e) indicates that the results of digital unfading are indeed superior to a standard RGB method in terms of color rendition. This is evident particularly in the more pleasing and natural (less magenta) rendition of facial color tones in the samples a and b. Similarly, in sample c, the result of digital unfading illustrates the absence of magenta cast on the legs of the model, an increase of color subtleties and a presumably more authentic saturation of the monstera plant in the background, compared to the supposed result obtained in conventional color grading. Furthermore, the degree of saturation and the magenta cast of the color chart in sample d, the facial tones, the red of the reference color chart and the details of the model's attire in sample e are also deemed critical in substantiating the recovery of correct colors. These inferences confirm the effectivity and potential of the spectral unfading approach compared to the arbitrary and subjective manipulation offered by the digital RGB re-grading tools.

To include a more objective comparison, the grayscale targets included in the China Girl samples were considered. The diagrams reported in Figure 4 contain colorimetric values corresponding to grayscale patches in sample a (top) and c (bottom). The CIELAB values [47] are projected on the a*–b* plane, so perfectly achromatic grayscales would lie in the center of the plots. In the two cases, the path from black to white is more "composed" and centrally positioned in the spectral approach when compared to the zigzagged path of the RGB adjustment.

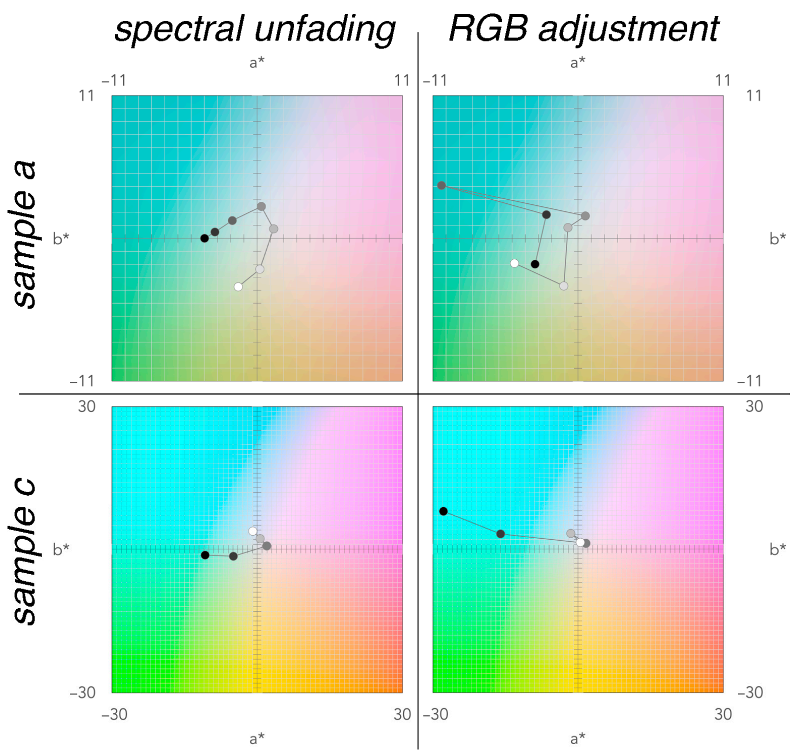

Figure 4. CIELAB values of the grayscale targets plotted in the a*–b* plane. The plots on the left report the result of spectral approach, while the plots on the right report result of the RGB tonal adjustment. Top: plots corresponding to sample a. Bottom: plots corresponding to sample c.

4. Discussion

Our proposed approach aims to restore the original color appearance of faded chromogenic photographic and film materials without employing subjective, historic or aesthetic assumptions about particular images' content, such as skin color, and in a much more refined manner than mere RGB re-adjustment in color grading. It is exclusively based on scientific knowledge and reasonable assumptions as starting points, such as the materiality and thus the spectral properties of the original color film at hand, and that either the frame lines between film images or image parts, such as the darkest patch of the color charts of the China Girls, were originally black. The latter assumption, in particular, allows us to derive the extent of relative fading of the dyes, while factoring in their unfaded spectra to reconstruct the original color image appearance. Based on this, the individual absorptions of the dyes are increased in the digital rendition to match the supposed original concentration, i.e., until the blacks appear to be black again.

In order to compare the digital unfading with the results a human operator could achieve via color grading, the subjectivity of the latter approach poses the challenge of making the two processes scientifically comparable. Presumably, a colorist would mainly focus on adjusting the skin tone and the white and black points in the process of grading. However, in the absence of references, such corrections would remain arbitrary and operator-dependent. Thus, to render the two results comparable, the "LUTgenerator" algorithm was employed (see Section 3), which minimizes the difference between the subjective RGB grading and the result of the spectra-based, digital unfading approach.

Eventually, further insights and improvements can be derived by future case studies dedicated to factors such as artificial aging in the pursuit of reliable before/after samples, applying the data derived from available Laboratory Aim Densities (LADs) to different images of the same reel or film print, comparing different prints of the same film and so forth through further refinement of the algorithm.

We consider the results shared in this publication as a promising demonstration of the potential of this novel digital image processing technique in the restoration and thus preservation of photographic and film color heritage.

5. Conclusions

The proposed digital restoration method is a material-based, quantitative spectral-approach to inferring the original optical properties of a faded chromogenic film and reconstructing the supposed appearance of its original, analog, theatrical projection. The validity of this method is based on the extraction of the residual color information present in the film with a RGB image capture. Prior knowledge about the analytical spectral densities of the photographic or film material (here, drawn from bibliographical resources) is a necessary requirement to develop the image processing technique of digital dye purification, which provides datasets corresponding to the original photochemical dye concentrations. The following steps of spectral reconstruction and color calculation allow us to finally reconstruct—to the best of our knowledge—the original color aesthetics of the now-faded film in a more scientific (and superior) manner than conventional and subjective digital color grading methods.

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Data Availability Statement: Input image files and the results of the restoration approach presented in this study are openly available at https://folk.ntnu.no/giorgiot/MDPI_Heritage2023.zip (accessed on 21 March 2023).

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