Modern methods for the visualization of lenticular film colors

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ABSTRACT

Some of the first home movies shot in color used a 16mm lenticular film produced by Kodak from 1928 to the late 1930s. This very special film stock called Kodacolor is embossed with an array of hundreds of vertical cylindrical lenses that allowed recording color scenes on a black-and-white panchromatic silver emulsion. There are multiple possible methods to extract the color information from the film images. Scanning the silver emulsion in high-resolution and letting a software extract the encoded color information represents an efficient method to obtain digital color images from these historical motion pictures. In this context, a new approach based on artificial intelligence has demonstrated to be more efficient for the localization of the lenticular screen than other previous methods. An alternative solution consists in digitizing the color images while these are created with the original optical method. While this last approach has the advantage of better representing the original historical appearance, it requires specific equipment and skilled operators.

KEYWORDS Lenticular film, Kodacolor, Color reconstruction, Deep learning, Film digitization

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1. Introduction

This paper presents and compares two novel approaches for reconstructing the color content of 16mm Kodacolor lenticular film. The first approach uses artificial intelligence to localize the color information in the digitized silver emulsion and provides a new modern tool to access lenticular films in color. The second approach reconstructs the color with an optical method, separating the color components by means of a moving slit that sections the entrance pupil of the imaging system used for the digitization. The close analogy with the original projection setup allows to consider the latter optical reconstruction a positive color reference.

2. Historical context of lenticular film

Since the birth of cinema in the mid 1890s, inventors and researchers set out to apply techniques of color photography to motion pictures. However, decades had to pass before a practical solution to record color information on motion pictures was developed.

In the 1920s the industrial exploitation of 'autonomous colors' such as tinting and toning was at its climax (Yumibe 2012), but at the same time a series of two- and three-color photographic processes were trying to improve their results and finally enter the market. Color processes based on temporal synthesis reunite color separations on the screen by displaying them in the same rapid succession as they have been recorded. The primary colors were added to the black and white separations either by filtering the projected light with a spinning filter wheel, as in Kinemacolor (Kindem, 1981), or by tinting the individual film frames, as in Friese-Greene (Bedding, 1909). Since the color separation images were taken at slightly different times, the reproduction suffered from pronounced color fringes around moving objects.

The lenticular film process, on the other hand, produced three color separations taken at the same time, and recorded them in a single film frame. Kodak was the only company that successfully produced lenticular film at an industrial scale. The film was marketed from 1928 under the name Kodacolor. However, most of the inventions behind the process have been made before the company acquired the rights to exploit the technique (Capstaff and Seymour, 1928).

The fundamental ideas behind the lenticular process for the photographic reproduction of colors can be found in the work done by Liesegang before the turn of the century (Ahriman, 1896) and by Lippmann a few years later (Lippmann, 1908). Liesegang envisioned a 'pixelated' spatial encoding of colors with a perforated screen, while Lippmann described in detail the structure of a lenticular film that would allow a better representation of reality. In the early 1900s Berthon combined the two concepts and started endeavoring the application of the lenticular color process to moving pictures (Berthon, 1910). In 1909 he patented a set-up including a tripartite red-green-blue filter as part of the imaging lens combined with a lenticular structure in front of the light sensitive panchromatic black-and-white film. The realization of this optical design had some major challenges. For instance, the lenticular structure engraved on the celluloid base defines the resolution of the image, so the lenticules had to be minuscule. For the technical implementation on an industrial scale, Berton found the assistance of Albert Keller-Dorian, who was the director of a company with expertise in engraving techniques (Jacquet-Loew, 1923). Berton intended to produce a film with minuscule lenticules either in a honeycomb-like shape (Fig. 1) or as a linear array (Berthon, 1910). The Keller-Dorian-Berthon process was patented in 1915 (Keller-Dorian and Berthon, 1914) but the first World War delayed the development. The cooperation continued until the death of Keller-Dorian in 1924, resulting in no more than some short experimental shots.

In 1926 a short film was successfully produced (Ede, 2013). However, the scarce success of the financial investment forced Berthon to sell the patents to Kodak, who instead managed to develop the Kodacolor film product in a comparably short time.

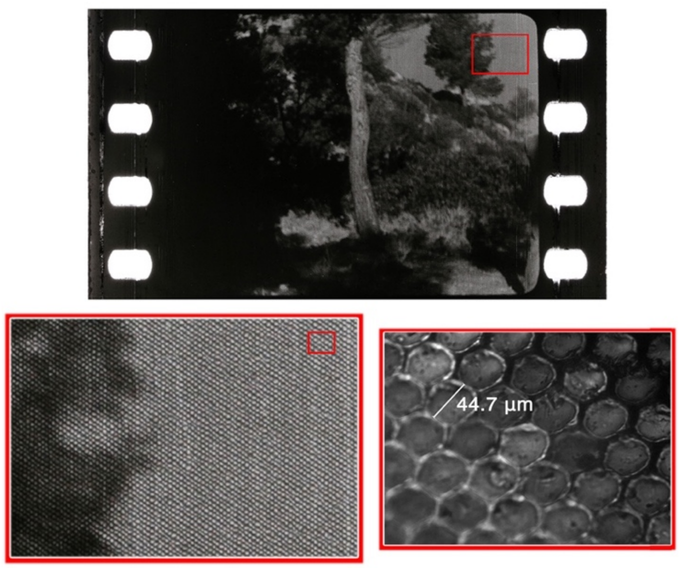

Fig. 1. A 35mm frame of a Keller-Dorian sample with a 'beehive' lenticular screen, visible in the underlying enlarged details.

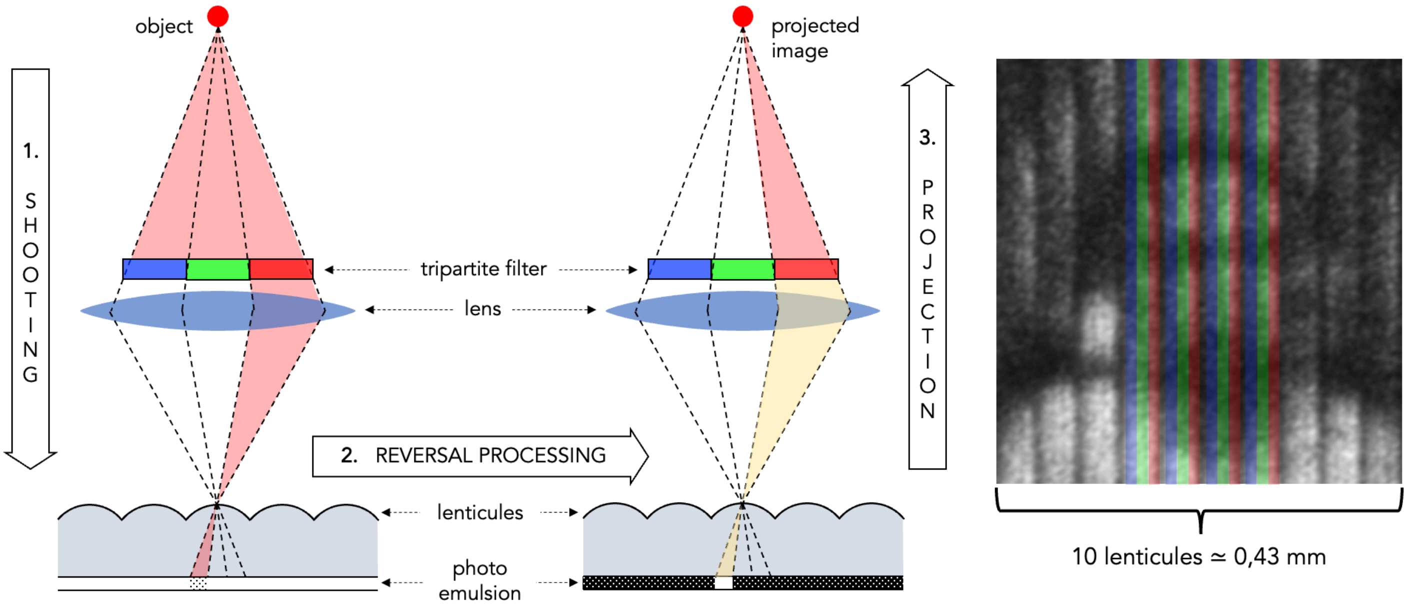

Fig. 2. Kodacolor lenticular film system – Left: Diagram describing the three stages of the lenticular color reproduction—shooting/processing/projection—for an 'object' represented by a red dot. Right: Front view of the processed photo-emulsion with superimposed stripes that indicate the location of the color separations.

The result was a 16mm reversal film with a linear vertical lenticular screen, aimed at amateurs, which was released in 1928. AGFA was working on a very similar product, called Agfacolor, which was ready to hit the market in 1932 (Eggert, 1932). However, no trace of any actual footage shot by amateurs could be found by the authors so far. The process was likely abandoned before its release.

A widespread market success was necessary for a novel color technique to survive for a sufficient time and have a significant impact on the landscape of cinema. If a new color process allowed to use existent hardware for film recording and projection, it had more chances of success (Jacquet-Loew, 1923), while additional costs of specific equipment—that could become obsolete in a short period of time—would likely dissuade exhibitors and amateurs alike to adopt novel processes. Also, the possibility of producing copies for distribution was an essential requisite for the success of a film technique (Mitchell, 1951). Kodacolor did not have these requirements, and it also had limitations in (i) image brightness—typical of all additive color processes—(ii) image detail and (iii) color gamut. After some success in amateur filmmaking, these limitations determined a quite sudden decline when a superior product was introduced by the same company. The introduction of chromogenic colors in the form of Kodachrome was a game changer for the film industry, and all other existing color processes on the amateur market rapidly disappeared. A wide color gamut could be reproduced by Kodachrome with subtractive synthesis, producing images with high level of detail using standard recording or projection equipment. Therefore, lenticular film rapidly lost appeal and Kodacolor disappeared from the market towards the end of the 1930s.

2. Characteristics of Kodacolor film

The lenticular system is based on the possibility to partition the entrance pupil of the lens into three separate parts, given the fact that the whole area of the entrance pupil uniformly contributes to the image formation. Additive primary colors (red, green, and blue) are assigned to each part using a tripartite color filter (Fig. 2-left). The camera lens focuses the image on the film and the color components are recombined, but their light arrives at the focal point from different directions. The tiny cylindrical lenticules focus the tripartite exit pupil of the camera lens on the film emulsion, so the color components expose separated areas of the film emulsion.

In the 10 mm wide image area of the 16mm Kodacolor film there are around 230 vertical lenticules. The motion picture was captured with the red-green-blue filter in front of the camera lens. The lenticules' focal length corresponds to the film thickness. A camera equipped with a 15 mm lens and a f/2 aperture allowed the color components to expose the photographic emulsion separately (Capstaff, Miller and Wilder, 1937). After exposure, reversal processing created positive silver-based images with spatially encoded color information:

the silver densities associated to the red, green, and blue components lie side-by-side underneath each lenticule (Fig. 2-right). The value of the color component is inversely correlated to the local amount of light-absorbing silver.

Fig. 3. Kodacolor ad suggesting a setting for the appreciation of the films (Movie Makers Magazine, 1928).

In the original procedure, the colors of lenticular film were displayed with a regular 16mm projector equipped with a tripartite filter similar to the one used during shooting. The projection was rather dim, and it could be only shown to a few people in a small projection setting (Fig. 3). Nowadays, the original filter attachments for cameras and projectors are hard to find, and analog projection is a threat to the unique reversal originals due to shrinkage and fragility of the film material. It is therefore difficult to display these films with the original procedure.

4. Numerical color reconstruction

The transformation of the image content into digital form enables a viable way to make these movies available to the public, while at the same time it preserves the image content that is otherwise subject to decay due to the aging of the film material. An efficient approach to obtain digital color images from lenticular film is to scan the film in high-resolution—with the emulsion facing the imaging system—and let a software extract the encoded color information. In 2013 two independent works were presented in different fora (Reuteler, Fornaro and Gschwind, 2013; Aschenbach, 2013), the first of which was conducted in the framework of the SNF project doLCE at the University of Basel. The software reconstructs the color accomplishing two main tasks: (1) the localization of the lenticular screen, and (2) the conversion of the side-by-side silver densities into RGB values.

4.1. Localization of lenticules' boundaries

The lenticular screen is quite clearly discernible as a regular vertical pattern overlaying the photographic image (Fig. 4-A). The numerical localization of the dark lines that mark the boundaries of the lenticules (Fig. 4-B) is essential to find and allocate the color information from a monochrome emulsion scan. The automatic localization with signal processing is sometimes complicated. The lines are not necessarily perfectly vertical and straight already from the film fabrication or became damaged and warped due to aging. Geometric distortions and defocusing might occur during scanning due to film misplacement or optical aberrations of the imaging system. In addition, the silver particles constituting the photographic image obscure the lenticular pattern in all dense areas of the image. The doLCE software positively localizes the lenticular borders and efficiently reconstructs the colors in certain cases (Reuteler and Gschwind, 2014). However, when the above-mentioned complications are relevant, the proper localization of the lenticular screen is error-prone and often fails.

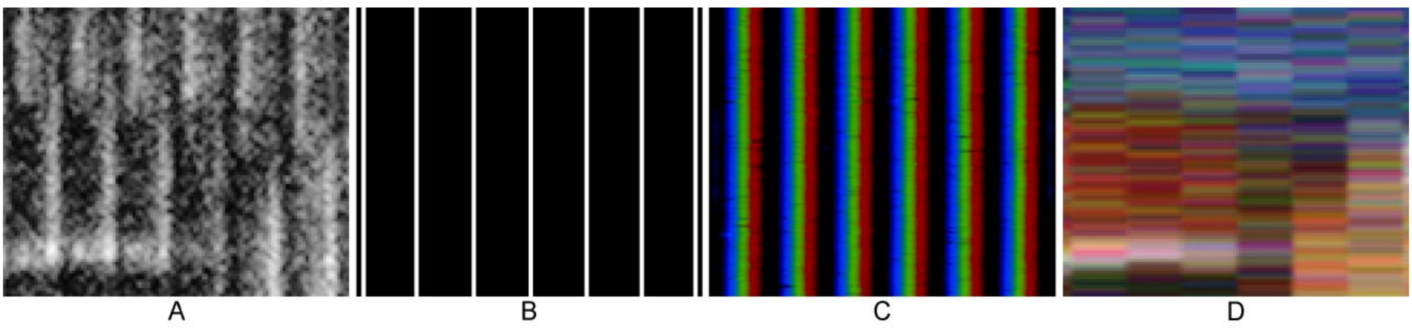

Fig. 4. The color reconstruction process – A: The input image. B: The lenticules' boundaries. C: The position of the color components. D: The final color image.

Instead of seeking to improve the success rate by introducing additional parameters to the existing software and making it more flexible, it was found convenient to adopt a completely different approach. A database of successful reconstructions carried out by doLCE was used to train a new computer algorithm called deep-doLCE (Trumpy *et al.*, 2021; D'Aronco *et al.*, under revision). The dataset of successful doLCE reconstructions was treated with techniques of data augmentation, so the training makes deep-doLCE able to handle the typical situations in which doLCE failed.

4.2. From grayscale to RGB

Once the lenticular boundaries have been accurately localized, the gray levels of the monochrome image (Fig. 4-A) have to be converted into color. This conversion is performed with a series of convolutions and pixel wise operations based on the spatial locations of the three color components (Fig. 4-C). The proper location of the color components with respect to the lenticule boundaries have been determined by recreating the original optical setup for projection and shining white light "backwards" inside the projection lens. In this experimental setup, the macro digital image reported in Fig. 4-C was captured from the emulsion side of the lenticular film.

The extracted RGB values are assigned to all the pixels localized within the lenticule in the specific row (Fig. 4-D), resulting in a pattern with horizontal stripes. The same 'stripy' pattern is also found in the images resulting from the optical color reconstruction.

5. Optical color reconstruction

An alternative approach to obtain the colors of lenticular film in digital form is to use an optical setup equivalent to the historical assembly. To perform the digitization directly, however, the color images must be focused on a much smaller area—corresponding to the image sensor—than the projection screen. The image structure of the color image captured in this configuration has the advantage of bearing a closer resemblance to the original projected image than the digital color reconstruction described in Sec. 4.

Nevertheless, the significant differences between the modern and the historical setups must be considered. The historical setup requires a wide-open lens aperture (f/2), otherwise the light intensities of the lateral red and blue components get attenuated in comparison to the central green. The large aperture was also an advantage for the lenticular process both in recording—due to the limited film speed—and in projection—due to the limited image brightness. In the modern setup for digitization, a macro lens with a wide-open aperture may produce a significant longitudinal chromatic aberration, such that it becomes impossible to find a common focus for all colors.

The problem caused by the chromatic aberration is solved with an approach that reconstructs the color by optical means, but it extracts the color components as separate images with the same spectral composition. Instead of replicating the original process with the tripartite color filter and a digital color sensor—as depicted in Fig. 5-A—a slit is used in front of the imaging lens, exploiting the fact that the color components of lenticular film are all black-and-white. The slit lets the light expose the sensor for one color component at a time, while the area corresponding to the other colors is covered. Three monochrome images are captured in succession with the slit in the three different positions, as depicted in Figs. 5-B. The digital images are assigned to their respective color channels (B1 to R, B2 to G, and B3 to B), so correct color images are obtained.

There is no focal mismatch between the color channels, and the longitudinal chromatic aberration is excluded by using a narrow band light source. In addition, the described method has the advantage that the exposure of the three images can be optimized independently. However, the digitization speed is reduced compared to the classical approach (Fig. 5-A), as three consecutive images have to be taken for each film frame.

While carrying out the described scanning operation, an accidental property of the information recorded by the lenticular system was made evident. In line with early Lippmann's idea (Lippmann, 1908), the horizontal difference in position between the blue and the red color channel produces a shift in perspective of the recorded image content. When the monochrome color separations are reproduced by assigning them to the left and the right eye respectively, the perceived image receives a moderate but clear stereoscopic effect. The lenticular process involuntarily records depth information which can be made visible today with stereoscopic visualization.

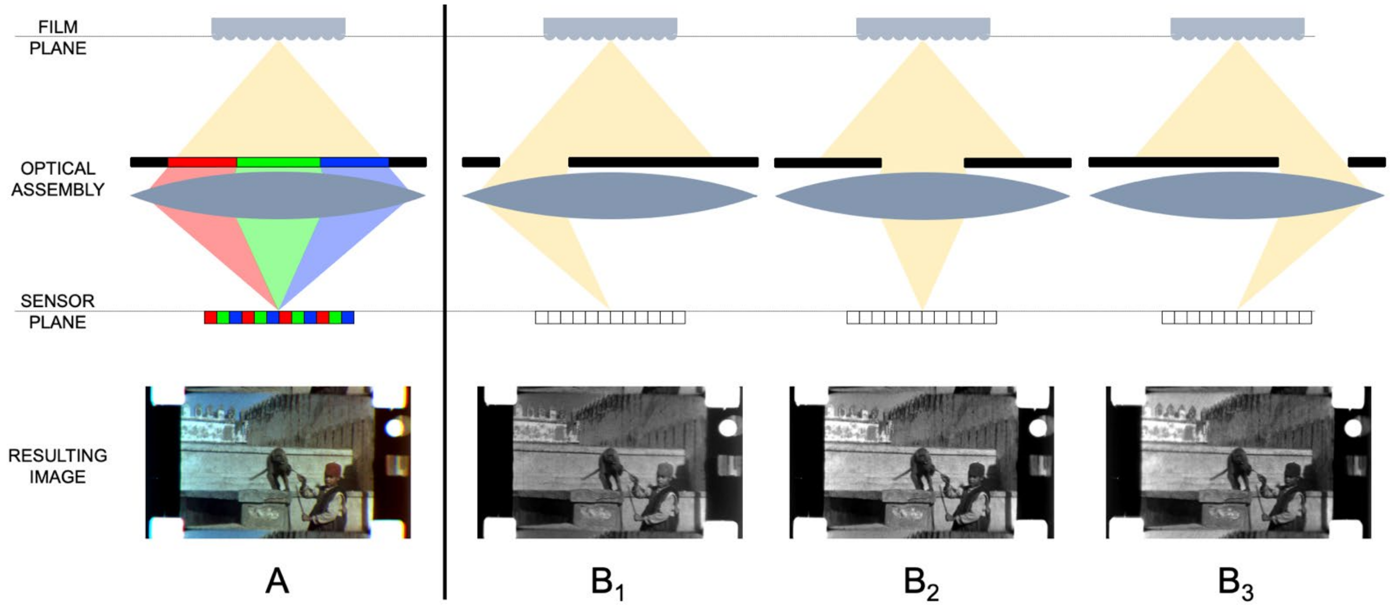

Fig. 5. Representation (not in scale) of the digitization process of the optically reconstructed lenticular color. A: Single image capture with a color image sensor and the tripartite color filter. B: Triple image capture with a monochrome image sensor and a moving slit.

6. Color correction

In order to obtain digital colors that properly represent the original analog projection of Kodacolor lenticular film, the images resulting from the digitization must be assigned to the proper RGB space. It is thus necessary to define the "*Kodacolor1928*" RGB space, which is calculated from the transmittances of the original color filter for projection. Transmission spectra were measured with a double-beam spectrophotometer (Shimadzu UV-1800) and colorimetric calculations (CIE, 2005) were performed considering the 1931 CIE 2° standard observer (CIE, 2019) and the irradiance spectrum of a typical film projector (Kinoton FP38), which was measured with a spectroradiometer (Konica Minolta CS-2000). The resulting CIE xy chromaticity values of Kodacolor1928 are R = [0.6991, 0.2900], G = [0.2569, 0.6687], B = [0.1399, 0.0704], and W = [0.2997, 0.3025]. The diagram in Fig. 6 displays the CIE 1976 UCS values (Hunt and Pointer, 2011) of Kodacolor1928 in comparison with DCI-P3 (SMPTE, 2011), which is commonly used in digital cinema projection.

In order to generate image files that convey the proper color information, the color values in the Kodacolor1928 space are converted to a standard RGB space for correct visualization. The whitepoint of the lenticular RGB space (XYZ = [0.991, 1, 1.315]) does not correspond to any standard whitepoint, therefore a chromatic adaptation transform (CAT) is necessary (Moroney *et al.*, 2002).

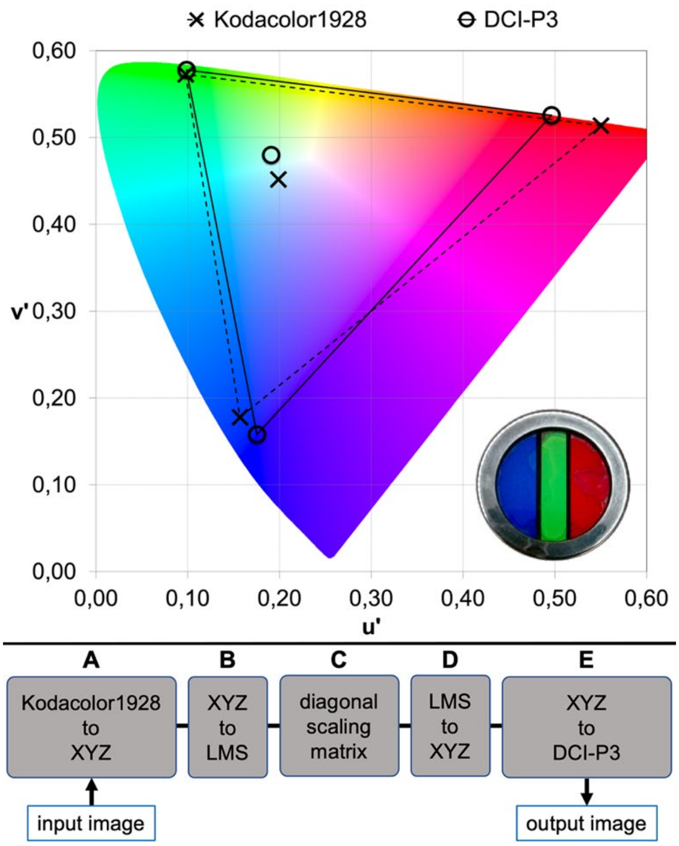

Fig. 6. Top: Chromaticity values of Kodacolor1928 space derived from the transmittances of the filter for projection (reported in the plot) in comparison with DCI-P3. Bottom: The five-step process for the color correction of digitized lenticular films.

In view of the linear von Kries model (Brill, 1995), the adaptation scaling must be performed at the cone response level (LMS), and therefore the color space conversion requires five steps, which are reported at the bottom of Fig. 6. The colorimetric specifications of Kodacolor1928 define the first 3-by-3 matrix, which provides the XYZ values of the RGB input image (step-A). The conversion from tristimulus to cone response and back (step-B and step-D) are the 3-by-3 matrices of the CIECAM02 Color Appearance Model (Moroney et al., 2002). The chromatic adaptation consists of the scaling factors resulting from the ratios between the LMS values of the destination and provenance whitepoints (step-C). In the present work we chose DCI-P3 as destination space, whose colorimetric specifications define the last 3-by-3 matrix (step-E) (SMPTE, 2011).

7. Results

The results of the methods described in the previous sections are reported in Fig. 7.

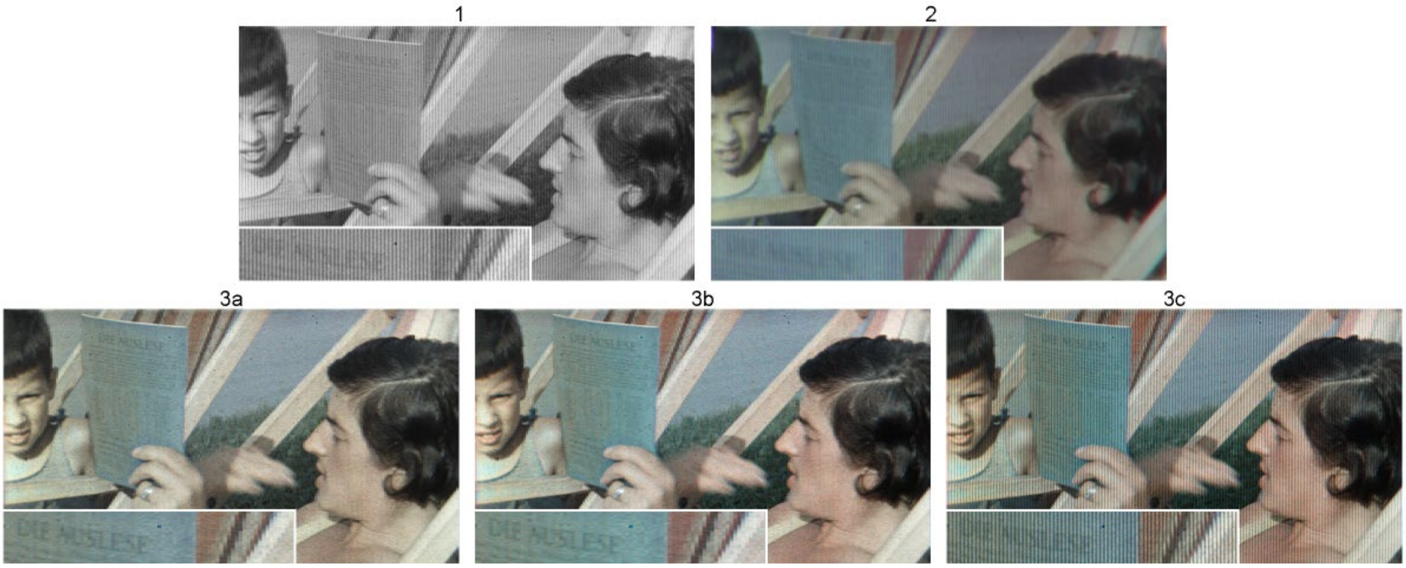

Fig. 7. Digital images of a lenticular film frame with inset enlargement. 1: Black-and-white scan of the film emulsion. 2: Slit scan. 3a: Output of deep-doLCE. 3b: Output of deep-doLCE after color correction. 3c: Merge of luminance from 1 and chrominance from 3b.

The scan of the film emulsion (Fig. 7-1) has an image structure that is characterized by the silver-based film grain and by the regular vertical pattern of the lenticules. In the color image resulting from the slit scan described in Sec. 5 (Fig. 7-2), the film grain is not visible, but the pattern of the lenticular screen is still evident. The image has a limited sharpness and the readability of the magazine title “DIE AUSLESE” is reduced. The color image resulting from the digital reconstruction with deep-doLCE described in Sec. 4 (Fig. 7-3a) has a very good readability, thanks to the effective interpolation approach developed by D’Aronco (D’Aronco *et al.*, under revision) and to the attenuation of the lenticular screen pattern. The color correction described in Sec. 6 (Fig. 7-3b) enhances the reds, owing to the prominence of the Kodacolor1928 space in the red region (Fig. 6-top).

Image 3b of Fig. 7 has a high level of image detail and accurate colors, but it lacks the image structure given by the film grain and the lenticular pattern. This situation suggests applying a method to transfer the image structure of the black-and-white scan to the color image. The method can be borrowed from video technology, separating the luminance and the chrominance using the YCrCb color space (Poynton, 2003). The extracted color information is converted to YCbCr, and the luminance channel Y is replaced with the black-and-white emulsion scan. This operation provides a ‘robust’ image structure to the image (Fig. 7-3c) that can be found appealing when the image is visualized on a big screen.

8. Conclusion

The projection of lenticular film with the original historical equipment is nowadays difficult to implement. Regardless of the approach adopted, the digitization of Kodacolor deliver a result that necessarily deviate from the original

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viewing experience. A bright, sharp image can raise concerns in terms of restoration ethics (Trumpy *et al.*, 2018), but it must be considered that the original screenings of lenticular film were always of poor quality and the new digital version can trigger a rediscovery of precious amatorial footage.

The close analogy between the original projection setup and the optical reconstruction described in Sec. 5 allows to consider the colors resulting from the optical reconstruction a positive reference (Fig. 7-2). Deep-doLCE provides a new modern tool to access the color of lenticular films and the resulting colors are sufficiently close to the reference (Figs. 7-3). The software is robust, successfully localizes the lenticular screen and provides convincing colors. As soon as the testing phase will be completed with more lenticular films, and the computational pipeline for final look of the reconstructed image is finalized, the software will be made available as an open-source project on publicly accessible repositories.

9. Conflict of interest declaration

No financial/personal interests have affected the authors' objectivity and potential conflicts do not exist.

10. Funding source declaration

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12. Short biography of the authors

David Pfluger holds a PhD in physical chemistry. After working in cinema post-production, he entered the field of time-based media preservation. He has been part of several projects in the field of film and video conservation. In the current Scan2Screen research project he is part of the technical team developing a multispectral film scanner specifically aimed at the challenges of color film preservation.

Lutz Garmsen - Filmmaker, media artist, designer, and lecturer for experimental and animated film. With a strong background in analog film and optical printing, since 2003 Lutz started working on experimental film digitizers. Since 2019 he collaborates with Prof. Barbara Flueckiger to design, test and improve a versatile multispectral scanner.

Giorgio Trumpy - Imaging Scientist with solid experience in bridging the gap between art and science. His fields of expertise span from optics to spectroscopy, from colorimetry to image processing, from heritage conservation to visual arts. Currently Associate Professor at NTNU and Research Scientist at the University of Zurich.

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