

Original research or treatment paper

A novel visualization tool for art history and conservation: Automated colorization of black and white archival photographs of works of art

**Sotirios A. Tsaftaris¹, Francesca Casadio², Jean-Louis Andral³,
Aggelos K. Katsaggelos⁴**

¹IMT, Institute for Advanced Studies, Lucca, Italy, ²The Art Institute of Chicago, Chicago, IL, USA, ³Musée Picasso, Antibes, France, ⁴Department of Electrical Engineering and Computer Science, Robert McCormick School of Engineering and Applied Science, Northwestern University, Evanston, IL, USA

This paper describes the use of a customized algorithm for the colorization of historical black and white photographs documenting earlier states of paintings. This study specifically focuses on Pablo Picasso's mid-century Mediterranean masterpiece *La Joie de Vivre*, 1946 (Musée Picasso, Antibes, France). The custom-designed algorithm allows computer-controlled spreading of color information on a digital image of black and white historical photographs to obtain accurate color renditions. Expert observation of the present state of the painting, coupled with stratigraphic information from cross sections allows the attribution of color information to selected pixels in the digitized images. The algorithm uses the localized color information and the grayscale intensities of the black and white historical photographs to formulate a set of equations for the missing color values of the remaining pixels. The computational resolution of such equations allows an accurate colorization that preserves brushwork and shading. This new method is proposed as a valuable alternative to the use of commercial software to apply flat areas of color, which is currently the most common practice for colorization efforts in the conservation community. Availability of such colorized images enhances the art-historical understanding of the works and might lead to better-informed treatment.

Keywords: Colorization algorithm, Pablo Picasso, Historical photographs, Image processing, Cultural heritage

Introduction

In the past two centuries art historical and conservation research have benefited from an important additional form of information: historical photographs of works of art in their final or intermediate states. These photographs are important historical artifacts: they can greatly assist research, and even serve as a record in the extreme case when the actual work may vanish or get destroyed. If the images show work in progress, they become a valuable tool for gaining in-depth knowledge on an artwork's genesis and the creative journey of their creators. Should treatment need arise these photographs are also very important working documents for conservators. Obviously, until the widespread introduction of

color photography these photos were usually black and white (B&W) and the lack of color information can limit a full understanding of the portrayed pieces, both from an art-historical and conservation perspective.

Initial attempts at adding color to B&W images in the museum setting involved a hand-colored replica. Today conservators, after digitizing the B&W photograph, typically rely on commercial photography software (such as Adobe Photoshop[®], Adobe Systems, Inc, San Jose, CA, USA) to digitally paint over the image. With this approach, the user utilizes several digital photo-editing tools (e.g. digital brushes, area fill tools etc.), to color the B&W photograph. The process requires significant time and manual effort, and unless special techniques are employed (transparent layers), adjusting the color tone to the underlying

Correspondence to: Francesca Casadio, Art Institute of Chicago, 111 S. Michigan Ave., Chicago 60603, IL, USA. Email: fcasadio@artice.edu

B&W intensity is not trivial and the brushstrokes of the original work are hardly preserved.

In this work a new customized method for automatic colorization of B&W photographs of works of art is presented. Colorization is a computer-assisted process of adding color to a monochrome image or movie. Colorization of historical artifacts such as black and white photographs, motion picture films, and cartoons has fascinated researchers and technology experts for nearly a century. The research in this field was driven by a consumer-oriented goal: colorization of black and white movies. The first colorized movies were cartoons, and the technique to accomplish this task was first introduced in the early twentieth century. Colorization of grayscale images as it is known today has been a research problem in the image processing community since the 1970s. The process, disclosed in a patent by Markle and Hunt, was first used in 1970 to colorize monochrome footage from the Apollo mission on the moon (Markle & Hunt, 1986).

Uses of computer-mediated methodologies in the cultural heritage domain have been broad; they range from using information technology for managing conservation and archaeology efforts to using interactive installations in museum exhibitions (Marty *et al.*, 2003; MacDonald, 2006). Within the context of conservation and cultural heritage it is possible to identify two main themes where computer vision and image analysis are used: (a) visualization and imaging techniques to digitize work; and, more relevant to this work, (b) uncovering lost or hidden information (Berns *et al.*, 2006; Palma *et al.*, 2010; Stork *et al.*, 2010; Johnson *et al.*, 2011a, b; Stanco *et al.*, 2011; Tsaftaris *et al.*, 2011).

The purpose of this article is to describe the process of colorizing historical black and white photos documenting earlier states of a painting using an automated approach that takes into account the underlying B&W intensity. The proposed approach requires minimal effort from the user who initially informs the algorithm on what colors to use. Its result is an optimized color rendering, driven by the underlying B&W intensities of the original photograph.

To illustrate this process, *La Joie de Vivre*, 1946, by Pablo Picasso (*LJDV*, Musée Picasso, Antibes, France 1946.1.4) is discussed as a case study. Archival pictures, taken between September and November 1946, show the artist at work on the painting and document several different states later obliterated or metamorphosed to form the image that meets the viewer's eyes today. The painting is on display at the Musée Picasso in Antibes, France, along with some of the historical photographs. The black and white photographs represent a unique resource to understand the artist's

working process; however, enabling visualization of the different states in color has the potential to significantly enhance the viewer's experience and might allow art historians to develop new ideas and make unprecedented connections with other paintings of that period in that same collection or elsewhere.

In this paper, first a description of the painting and its evolution is given in order to provide an insight on how Picasso radically transformed his artwork. Then the customized colorization algorithm and the process with which color information was extracted from the painting as it appears today are described. The inherent limitations of the process, which are directly related to the quality of the original photographs, are also illustrated. To this end, a discussion is offered on issues of illumination in the original photographs and how those need to be corrected in some cases in order to have a historically accurate colorization. Finally, the new colorized photographs are presented and conclusions are drawn as to their art historical significance and their value-added in fostering a dialogue among image processing experts, curators, and conservation scientists.

La Joie de Vivre: history and significance

Undoubtedly the most famous and iconic painting in the Picasso collection of the Antibes Museum, *La Joie de Vivre* is also its most emblematic. Its subject matter somehow distills the general character of this group of works executed in the Grimaldi castle in the autumn of 1946. It is well known that after the dark years of war Picasso rediscovered the Mediterranean sea, luminous not only by virtue of its ancient and mythological suns, but also enlivened by a new breath of fresh air, both artistic and personal: the artist was now accompanied by a young woman, 40 years his junior, who would soon make him a father again (Gilot & Lake, 1964). That is, in essence, the *Joy of Life (La Joie de Vivre) (LJDV)*: Françoise Gilot, depicted as the central nymph dancing in front of an Eden-like landscape of water and earth, accompanied by a faun and a centaur playing the double flute and two small goats (Fig. 1). The title given to this large fibrocement panel (120 × 250 cm) by Dor de la Souchère, director of the museum at the time and the first to exhibit this major Picasso work (Giraudy, 1981–2, p. 2) perfectly encapsulates this celebration of a newfound freedom and of creative renewal. This painting is also quite unique among the collections of the museum because it is without doubt the one on which Picasso labored for the longest time during his short two-month period of work in the Antibes castle. That the artist practically worked on it from the beginning to the end of his stay is confirmed by the numerous photographs taken by Michel Sima in



Figure 1 Pablo Picasso, *La Joie de Vivre*, 1946 (Musée Picasso, Antibes, France, 1946.1.4); oleoresinous enamel paint and charcoal on fibrocement, 120 × 250 cm. Present state ©Emilie Hubert, CICRP, Marseille (Photo) ©Estate of Pablo Picasso/Artists Rights Society (ARS), New York.

the spacious room on the second floor of the south wing that was used by Picasso as a studio. Michel Sima, an artist in his own right, had recently returned to France as a survivor from Nazis concentration camps. A sculptor and a photographer, he was working in the top floor of the Grimaldi castle before Picasso became its most famous artist in residence, and documented the work of Picasso with hundreds of photographs, taken virtually every day (Sima *et al.*, 2009). *LJDV* is often pictured propped on the easel where it was being painted, surrounded by other paintings executed at the same time. This important historical photo documentation reveals at least four different and consecutive states of the painting leading to the present day image. The nearly film-like sequence of photographs enables the reconstruction of the creative process of the artist, revealing the dynamic tension between the work and its creator, going as far as possibly suggesting that the painting opposed some resistance to its maker for quite some time. Although upon close observation a dozen of photographs show small modifications of the figures, the four images at the center of this discussion were selected in concert with the Museum's director as the most significant art-historically, while many of the others merely represent the daily process of painting. Studying these four significant stages in the evolution of this masterpiece one realizes that the main compositional choices are never called into question: the central figure of the nymph, the centaur on her right and the two goats and the faun on her left remain fixed, with a ship sailing away on the horizon line; however, the figures are profoundly modified. Overall one notices a progressive reduction of the

size of the heads, especially that of the dancing nymph, whose chest widens as she loses her robe, her bottom more precisely delineated and her legs endowed with feet, while the fortified walls in the background at right disappear to allow the extension of the horizon line. Eventually, the foliage in the lower left corner by the centaur gives way to a stylized plant, which echoes a splash of grass on the upper right corner.

The photographs taken by Sima inside the artist's studio, using an analog camera of unknown make and model with a makeshift bamboo cane piece as stopper, glass plate negatives, and movie set lights as illumination sources, constitute the basis of this attempt to apply computational algorithms to obtain an objective representation of the different states of *La Joie de Vivre* in color.

Methodology

Digitizing LJDV and the historical photographs

Digital representations of works of art have become immensely useful for scholarly research and conservation of cultural heritage, facilitating collaboration among different groups that may not share the same location and aiding in the study, preservation, or restoration of the work itself (Barni *et al.*, 2005; Berns *et al.*, 2006).

The digital image of the present state of *LJDV* (which is labeled **P** here for this day) is the result of a single photograph acquired in 2009 with a digital SLR camera. The camera was placed on a tripod and a color checker color rendition chart (X-Rite Inc, Grand Rapids, MI, USA) was used to calibrate the digital image. The Sima photographs (termed

here S_i for Sima, where i is one of the four photographs selected for this experiment) were digitally scanned from Sima's glass negatives using a desktop scanner at 1200 dpi resolution and 16-bit depth. To facilitate comparison and further research, the digital images – which often included a portrait of the artist or a portion of the studio – were manually cropped to retain only the painting (Figs. 2 and 3).

A painting colorization algorithm

The requirements for painting colorization are different than those concerning the usual applications of colorization to commercial images like movies or cartoons: high accuracy and fidelity are necessary and because the image formation model differs significantly from natural or cartoon images the customized colorization algorithm needs to be adapted and tailored to the specific style of the artist. For example, abstract and cubist works have a completely different, less naturalistic style compared to Renaissance or Impressionist works and thus require different pre-treatment. Furthermore, in general one cannot assume as in portrait photography that the foliage of a tree may be reasonably green or a stretch of water blue.

The optimization-based colorization algorithm aims at colorizing an image using a few predefined color hints. Fig. 4 provides a graphical overview of the automated process utilized here. Briefly described, the method used for colorization (Tsaftaris *et al.*, 2011), which is an adaptation of the one proposed by Levin *et al.* (2004), relies on the fact that the color information at specific locations (termed color hints) is defined *a priori* by the user or through color transfer methods such as statistical correlation of pairs of images (Tsaftaris *et al.*, 2011). The basic premise of the algorithm is that pixels with similar luminance values will have similar chrominance values. Since the grayscale intensities (i.e. the luminance) are given in the B&W photographs the goal is to find the color (chrominance values). This process is easily applied if a color-space that separates luminance and chrominance components is used. There are several such candidate color spaces (YUV, YCbCr, YIQ, Lab). For the following description, a YUV color space is assumed. The YUV color space represents every pixel in three components: one for luminance (Y), and two for chrominance (U and V). Thus, the goal is to estimate the U and V components using only the intensity component Y, which in this case is given by one of the Sima images, and color 'hints', which are described in the following section. Details of the estimation of the U and V components are described in Appendix 1. Once the hints and input (Y) image are available, the method proceeds automatically, estimates U and V using the colorization

algorithm, and then finally produces the composite colorized image (Fig. 4). Throughout the whole process the only human intervention is in providing the color hints and performing an expert visual assessment of the outcome of colorization.

To colorize *LJDV* all computational and estimation operations were performed in Matlab (Mathworks, Inc, Natick, MA, USA); and results were visualized using Adobe Photoshop® with the same color profile used to create hints (Adobe sRGB). The process followed an iterative pathway, initially performing all operations on low-resolution images to fine tune placement of color hints and other parameters. In fact, due to the high resolution and size of the original images (measuring between 14 and 68.5 MB at 300 dpi) the complexity of the optimization problem at hand was significant. To obtain a final high-resolution colorized image, it was necessary to utilize a computer node from Northwestern University's computational cluster with 64 GB of memory and a quad core Intel XEON CPU. As a frame of reference it should be pointed out that a low-resolution version of an image (usually one-fourth of the original size) needed approximately ten minutes of processing time and the algorithm had a 2-GB memory footprint requirement. At full image resolution the same algorithm required 30 minutes for processing time and had 12 GB of memory footprint.

Identifying color hints

The availability of localized information on the original color of buried passages (or color hint) is crucial for the success of any colorization effort. For this case study, two sources of 'hints' were available: those derived from close observation of the painted surface, especially in areas of loss or where an underlying layer had not been completely obliterated (Figs. 5 and 6) and those inferred from observation of cross sections of paint samples (Fig. 7). Although the most recent campaign of investigation of *LJDV* was carried out non-invasively (Casadio *et al.*, 2013), five historical samples taken in the 1980s from the left half of the painting and conserved at the Centre de Recherche et de Restauration des Musées de France (C2RMF, Paris), were made available for this research. These samples showed some of the underlying layers of paint and thus provided additional color information for the areas where the cross sections were taken.

Meticulous and close examination of the surface of the painting with the naked eye also revealed several areas that Picasso retained throughout the composition or did not cover completely, which could be correlated to specific passages in the historical photographs of the different states. These visual

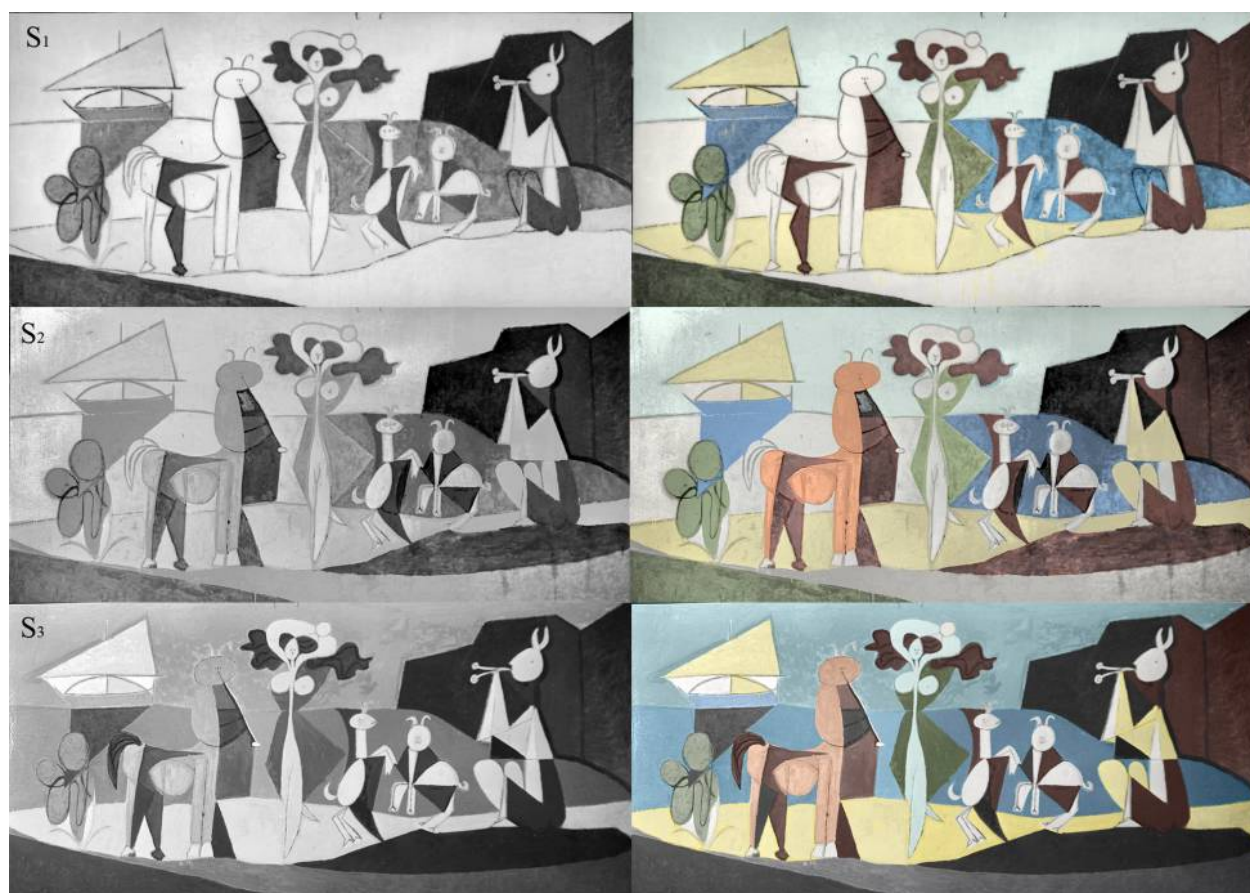


Figure 2 S1, S2, S3: 1946 photographs by Michel Sima illustrating the first, second, and third state of *La Joie de Vivre* (©Michel Sima heirs). On the right: results of colorization for each corresponding image.

observations were enhanced by an extensive campaign that used X-ray fluorescence spectroscopy (XRF) to probe the pigment composition of all paints used by Picasso in Antibes (Picasso, 2011). When applied to paintings the XRF technique extracts elemental information from a so-called ‘interaction volume’ that often comprises all painting layers down to the substrate. Thus, sometimes color information of overpainted layers could be inferred or confirmed based on the elements detected with XRF analysis. The process of estimating the actual color of buried layers and obtaining an accurate color reconstruction was further facilitated by the fact that Picasso used a limited set of commercial enamel paints for all the paintings and painted works on paper in Antibes. He applied relatively pure colors drawn from cans of ready-mixed paints mostly with flat, minimally blended applications. Thus, most of the colors of the buried passages can be found again in various areas of the painting as it appears today.

Once the color hints are identified for all the distinct areas that need colorization the process of transferring them onto the digital image of the historical photograph is fairly simple, albeit somewhat time consuming and rather tedious when performed by a human operator. However, this step is necessary with all colorization algorithms and requires much less time than

the coloring of the entire image using classical approaches. On occasions, when artists incorporate significant passages of the underlying compositions into the final image, statistical correlation algorithms can be used to identify areas of similarities between the final and previous states of a painting (Tsaftaris *et al.*, 2011). In such cases color hints can be automatically extracted from the image of the work in its present state and transferred on the historical photographs in an automated manner. This was not possible with *LJDV*, where buried layers often show only as small remnants of brushstrokes that were not completely covered, with few exceptions such as the long and narrow stretch of sandy yellow beach in the middle ground. Therefore, in this case a human operator was needed. Adobe Photoshop®’s eyedropper and pencil tools were used to respectively extract color hints from previously identified pixels in the color image of the present state and transfer them onto the black and white Sima photographs. Because *LJDV* is painted with broad applications of color with minimal mixing and blending, the placing of color hints was much simplified. In fact, within areas painted with the same color it was possible to arbitrarily create scribbles of the hues to be used for colorization, given the minimal variation between adjacent brushstrokes for same-colored passages. This approach

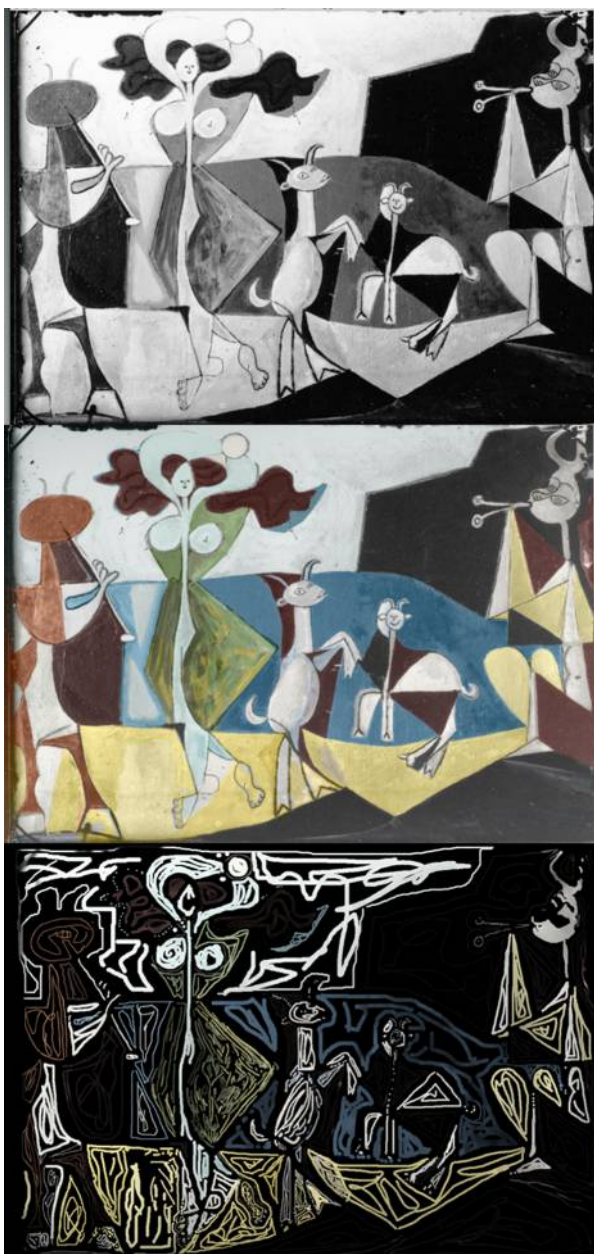


Figure 3 Top: 1946 photograph by Michel Sima illustrating the fourth state of *La Joie de Vivre* (©Michel Sima heirs). Middle: the result of colorization. Bottom: the image with 'hints' used by the colorization algorithm to spread color on the historical black and white image reproduced at top.

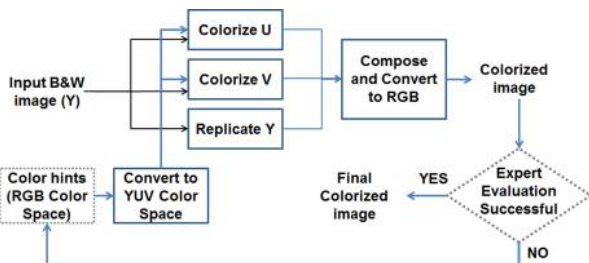


Figure 4 A diagram illustrating the colorization process. All steps are automated and do not require any operator input, except the color hints and visual assessment (shown with dotted outlines).



Figure 5 *La Joie de Vivre*, 1946: detail of the central figure of the dancing nymph, showing remnants of her previous green robe.

would not be appropriate for paintings with extensive shading, wet in wet mixing, and other types of application where there is extreme variation between one brushstroke and the next: in such cases, one could only assign colors to discrete pixels. An example of the Adobe Photoshop[®] template used to re-colorize image *S*₄ is illustrated in the bottom panel of Fig. 3.

Adjusting for illumination and film saturation

The historical photographs by Sima were taken under a wide variety of lighting conditions: in full daylight, at night with strong artificial illumination produced by a



Figure 6 *La Joie de Vivre*, 1946: detail of the boat at upper left illustrating the light blue color of the sky before it was covered with white.

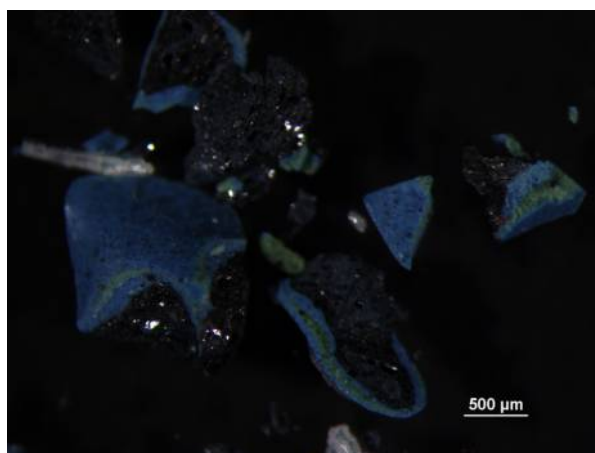


Figure 7 Stereomicrograph of a sample taken from the sea below the sailboat at upper left, showing evidence of several campaigns of paint, including the black layer illustrated in the colorized version of the third state (S3).

point-source, and with light often impinging on the painting at an angle. All these aspects can affect the results of the colorization process, whose quality and accuracy can never exceed that of the originals. Although the majority of the images could be colorized without any manipulation of the grayscale intensities so as not to alter original historical artifacts, one particular photograph (depicting the fourth state, or S_4) had significant illumination distortions. As can be observed in Fig. 3 the hair of the dancing nymph (Françoise) appears lighter on her proper right than it is on her left, while it should have the same intensity and tone on both sides in the historical photograph as it has today, given that it did not undergo any further changes from the fourth to the final state. A potential source of this distortion is improper exposure and development of the glass plate. In order to achieve the most accurate approximation of the original colors of the painting such distortion had to be corrected as not doing so would have prohibited the colorization of S_4 . Prior to correcting for the illumination distortion, S_4 was registered to the grayscale version of the present state. The registration enables the direct comparison of regional intensity values between the two images, and the correction of the distortion in illumination. This process is outlined in Appendix 2. Finally, once illumination distortions were fully corrected, the adjusted S_4 image was used as the grayscale input to the method described in the previous sections.

Results and discussion

The colorized photographs

The procedures outlined above were used to create color hints for each of the Sima B&W photographs. An example of such color hint image is shown in the bottom panel of Fig. 3.

Subsequently the customized colorization algorithm was used to automatically distribute color on each Sima image, preserving brushwork, accuracy of hue, and subtle shading in a computer-controlled way. The quality of any colorization process depends on the accuracy of the color hints, the quality of the input grayscale image (especially concerning image resolution and fidelity in reproducing luminance), and the accuracy of the colorization algorithm. Because the first two parameters are strictly dependent on the degree of information available in the painting and the historical photographs, respectively, the only parameter that can be optimized is the colorization algorithm. To quantitatively validate the accuracy of the colorization algorithm re-coloring of the present state image was pursued, following the strategy described in Tsaftaris *et al.* (2011). The present day image was used as ‘ground truth’ colored image, and its grayscale version (luminance only component) as the input B&W image. By randomly transferring some of the original color pixels to the input B&W image color hints were obtained. Using these hints the B&W image was colorized using the proposed algorithm, and the error measured between the estimated color and the ground truth color version for all pixels. In a Monte Carlo fashion (Saltelli *et al.*, 2008), i.e. by randomly choosing a variable set of pixels that retain the original color to generate several color hint images, this process can be repeated several times and the resulting error can be recorded. Several random repetitions can quickly create an assessment of the overall performance of the colorization algorithm, without having to go through all the possible pixel combinations, a task that is computationally unfeasible.

Fig. 8 shows an example of this colorization validation for a detail around the central nymph in the present day image. Qualitatively, one can observe that the algorithm is capable of colorizing the image with high accuracy and just a few color hints. This is also demonstrated quantitatively using Monte Carlo analysis. Fig. 9 shows the effect of hint coverage (i.e. the percentage of pixels in the image that have a known color) and the corresponding error. The error here is obtained by calculating the average absolute error across the colors R, G, B, normalized by the maximum error (255), according to the following equation: $|red(true) - red(estimated)| + |green(true) - green(estimated)| + |blue(true) - blue(estimated)| / (3 * 255)$. Evidently the more widespread the color hints the lower the error; however, after 10% of coverage the error falls below 1.7%. This means that on average the colorization algorithm estimates colors which are only approximately 2% off from the original color value, using only 10% of hints. In addition after 10% coverage the vertical variance (i.e. the degree of

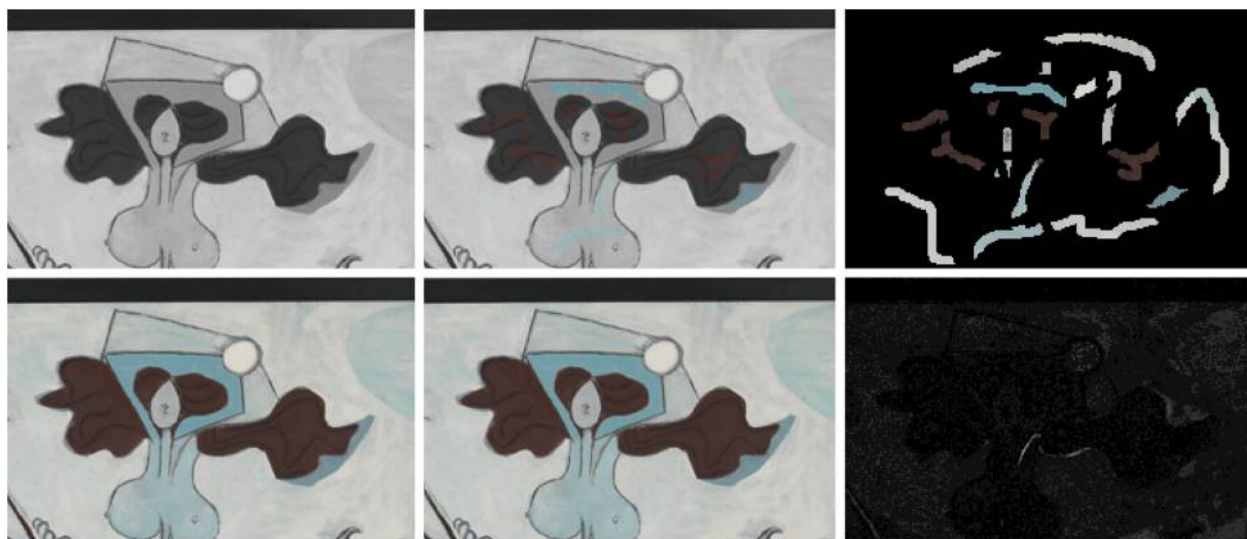


Figure 8 Validation of the accuracy of the colorization algorithm. Detail (around the head of the nymph) of colorizing the present day image of the painting. Top row from left to right shows the grayscale version of the image, the same image with the color hints superimposed, and the color hints corresponding to this area. Bottom row from left to right shows the original color version of the image, the result of colorizing the grayscale image (top left) with the hints (top right), and finally the absolute error (black: zero error, white: 255) obtained by subtracting the two color images (bottom right). The algorithm accurately reconstructs the missing colors using just a few color hints in an unbiased and quantitative fashion. The average absolute error in this case is 1.7%.

scattering of the data points above and below the curve) becomes smaller than at lower coverage. This signifies that after 10% coverage the placement of color hints does not significantly affect the result of the algorithm. The evidence described above demonstrates that the used algorithm is not particularly sensitive to the exact placement of hints, requires a small number of hints and has overall color-accuracy as assessed both qualitatively and quantitatively.

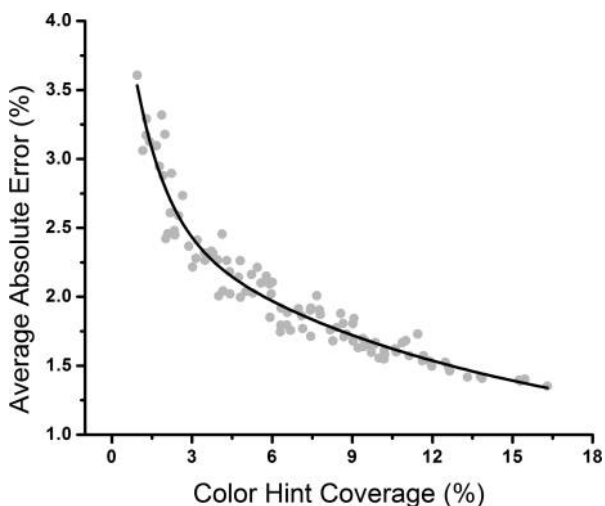


Figure 9 Monte Carlo analysis showing the effect of color hint coverage (i.e., the percentage of pixels with known color) on the average absolute error between colorized image and its original color. Each data point reflects an experiment with a random set of color hints (of a given total coverage) and the corresponding error (shown as percent of the color value of the color-space). Within the same graph an exponential line fit is shown for reference.

A panel showing the final colorized Sima photographs is shown in Figs. 2 and 3. The colorized result is smooth, has limited color bleeding, and was deemed of high verisimilitude and useful to open new perspectives for art historical research. Some of the thick overpaint particularly evident in the bottom part of the painting and in the faun at right renders the nature of previous colors harder to extrapolate for these passages, causing results on selected areas to still remain speculative. Only further, extensive sampling could provide unambiguous answers to the open questions of this colorization experiment, but ethically this would be hard to justify given the



Figure 10 A detail of the fourth state of *LJDV* colorized with the automated algorithm (left), and with manual application of color through Adobe Photoshop® tools by a human operator (right).

exceptional condition of the work. In any case, the images illustrated in Figs. 2 and 3 remain extremely valuable close approximations that for the first time allow full appreciation of the rhythmic chromatic permutations of this masterpiece. By way of comparison, Fig. 10 illustrates a detail of *S₄* colorized with the automated algorithm described here (at left), as opposed to the more traditional, more subjective, and labor intensive colorization using Adobe Photoshop[®] tools by a manual operator. It is apparent that the manually colored image results in a rather flat, dull, and less color-accurate rendition, due to the need of adjusting transparency of the layers (typically set at 60–75%) to reproduce some shading: leading to a generally less satisfactory result.

Art-historical interpretation of the colorized images

From an art historical perspective, the new colorization allows an enhanced understanding of the chromatic evolution of *La Joie de Vivre*. The newly acquired color information reinforces the conclusions gleaned by studying the formal composition and placement of forms in black and white: that the starting principles are maintained throughout, with the staging, from bottom to top, of four distinct color bands. Gray and black are placed at the base, then a yellow colored band to evoke the beach, then a blue for the sea and another for the sky, the latter eventually covered in white when Picasso decided to erase the fortification in the background. Yet the original rusty ochre of the centaur did not survive, now a mere glimpse at the extremities of its forelegs, and the faun on the right on losing its horns gets colored in green and blue. The balance of the greens is completely reversed going from the first to the present state, reduced to essentiality when moved from the robe of the dancing nymph to a small sliver on the dancing goat, and, most dramatically, when the green organic shape at bottom left gets distilled into an arid and stick-like plant with minimal traces of green. At first glance, when compared to the final state, the numerous variations undergone by the painting make one wonder if the work always benefited from such changes. What is certain is that the thickness of the overpaints bears testimony to the long history of the titanic battle between the work and its maker, and one might even wonder whether the succession of states might not have been prolonged, had the artist been able to bring the large painting with him to Paris upon leaving Antibes in the middle of November 1946. Instead, the work was left in place with the majority of Picasso's production in Antibes, where the stroke of genius leading to its christening with a title that evokes a long bygone era of heroic painting and the glories of times past, surely

contributed significantly to its fortune with the critics and enormous success with the public.

Conclusions

Painting colorization is a particularly interesting application since it imposes significant requirements on the accuracy and precision of the color transfer process. It offers a unique exploration and visualization tool for art historians and conservators that can sometimes lead to revelatory consequences.

The new method proposed here is described as a valuable alternative to the use of commercial software to apply flat areas of color (with minimal modulation achieved only by varying layer transparency), which is currently the most common practice for colorization efforts in the conservation community. The colorization approach described here also requires less effort by the human operator compared to current practice, since rather than having to apply color manually in all areas, only a few color hints are necessary. This amounts to significant time savings and renders a more realistic and less biased outcome since color is spread using optimization routines and the user interaction is small.

Although this paper illustrates a state of the art colorization algorithm adapted for painting colorization with successful application to a modern masterpiece by Pablo Picasso, further developments can facilitate the application and accuracy of similar colorization techniques. For example, current approaches do not easily accommodate common practices by artists, such as blending of several brushstrokes of different colors. Automated image registration and color transfer methods that can transfer color from digital representations of the present state of paintings to B&W photos without the need for registration will reduce human input and labor involved in providing color hints.

Any protocol optimized for painting colorization will always benefit from expert input as advice, as the process deals with the colorization of important historical artifacts. In essence, the tool proposed here is not intended to replace the 'expert', but rather facilitate the colorization of such artifacts with highly automated and minimally biased means.

Acknowledgements

We are thankful to Isabelle Le Druillennec and all the technical staff at the Musée Picasso, Antibes for their invaluable practical assistance when examining the painting. Roland May and Emilie Hubert of the Centre Interrégional de Conservation et Restauration du Patrimoine (CICRP, Marseille) are thanked for providing high resolution direct light image captures of *LJDV*. The heirs of Michel Sima are thanked for access to the high resolution scans of the original

glass negatives. Gilles Barabant, Béatrice Sarrazin, Nathalie Balcar, and colleagues at the Centre de Recherche et de Restauration des Musées de France (C2RMF) are thanked for granting access to the historical samples and archival technical information on the Antibes samples. Gwénaëlle Gautier and Benoît Dagron are also thanked for sharing their insights and observations on Picasso's painting practice in Antibes.

Appendix 1
Technical details of the colorization process

In the following, since the procedure is the same for both U and V components, only the procedure for determining U is presented.

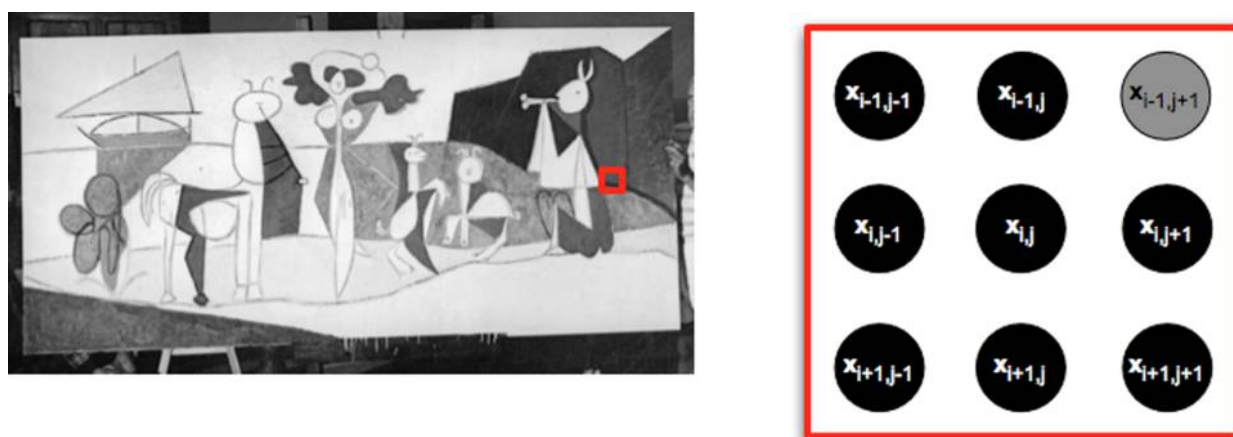
A linear optimization problem is cast with respect to the pixels with unknown color component (e.g. U) in a 3 × 3 pixel neighborhood around the pixels with known color (Fig. 11 illustrates an example). Once all pixels in the B&W image have been considered and equations have been cast for all of them, the solution to the problem can be had by solving the system of linear equations. This process thus allows the U and V chrominance components to be estimated for all the pixels in the historical photographs, using only the Y component (the grayscale image) and the color hints. It is important to note that the color hints are converted to the YUV space and only their U and V values are retained, which are then used in the colorization process. Thus, the final color of the composite image depends on solving the linear

equations above and on the luminance component of the input image. This results in a composite image that maintains the luminance of the original image, but is now in color.

Appendix 2
Technical details of illumination adjustments

The Scale Invariant Feature Transform method was used to find matching points between the two images S_4 and present day (Lowe, 1999; Vedaldi & Fulkerson, 2008). Then, the method described in Arganda-Carreras *et al.* (2006) was used to complete the registration process. Subsequently, following a similar approach as that discussed by Styner *et al.* (2000), to estimate the illumination distortion, an illumination field F modeled as a smoothly varying polynomial field composed of Legendre polynomials up to third degree was assumed.

Assuming an additive illumination field the field F was estimated based on the relationship $X \propto F + X'$ (with '+' denoting point wise addition), where X is the S_4 image, and X' is the desired corrected image. The pixels in the S_4 image above a certain threshold, set as 70% of the maximum intensity were selected to estimate the field F . Upon estimation, the corrected image could be recovered based on the following equation: $X' = X - F$. The estimated field F is shown in Fig. 12. At this point, a further normalization step of the intensities of X' was required. This was achieved by comparing the average intensity of the hand-drum held up by Françoise in the final state with that of



$$\begin{aligned}
 & a_{i-1,j-1} \cdot x_{i-1,j-1} + a_{i-1,j} \cdot x_{i-1,j} + a_{i-1,j+1} \cdot x_{i-1,j+1} + \\
 & a_{i,j-1} \cdot x_{i,j-1} + a_{i,j} \cdot x_{i,j} + a_{i,j+1} \cdot x_{i,j+1} + \\
 & a_{i+1,j-1} \cdot x_{i+1,j-1} + a_{i+1,j} \cdot x_{i+1,j} + a_{i+1,j+1} \cdot x_{i+1,j+1} = 0
 \end{aligned}$$

Figure 11 The colorization algorithm develops a set of equations for each 3 × 3 neighborhood of pixels (right) in the unknown chrominance matrix. Here for illustration purposes the top-right pixel ($x_{i-1,j+1}$) is shown in gray, to denote that for this pixel the color information is known. Centered on a pixel location i,j , the algorithm builds these equations (bottom) as a weighted sum of the neighborhood's unknown (or known) chrominance (color) values. The coefficients $a_{i',j'}$ are derived based on the known grayscale intensities between the center pixel (i,j) and its neighbor (i',j'); they are a function of how similar these intensities are. The total sum of all $a_{i',j'}$ in the neighborhood is one.

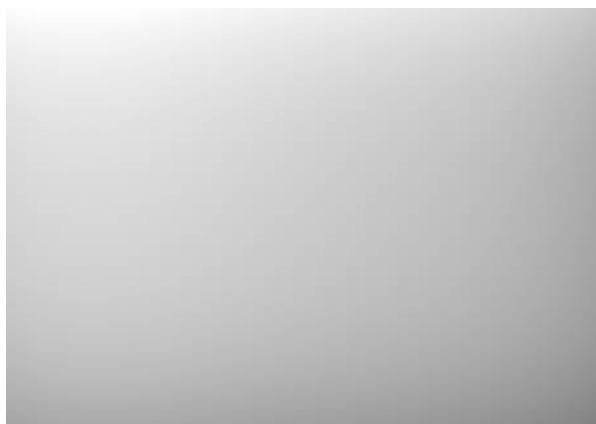


Figure 12 Illumination field as estimated using the approach described in text corresponding to the fourth state, shown in Fig. 3.

the historical photograph. This present day intensity value was subtracted globally from the pixel intensities of X' to obtain X'' , in order to have a match between the intensities of that detail in the historical and present day photograph. X'' is the S_4 image where all illumination distortions are fully corrected, and it is the image that was colorized with the method described in the paper.

References

- Arganda-Carreras, I., Sorzano, C., Marabini, R., Carazo, J., Ortiz-de-Solorzano, C. & Kybic, J. 2006. Consistent and Elastic Registration of Histological Sections Using Vector-Spline Regularization. In: R. Beichel & M. Sonka, eds. *Computer Vision Approaches to Medical Image Analysis*. Berlin/Heidelberg: Springer, vol. 4241, pp. 85–95.
- Barni, M., Pelagotti, A. & Piva, A. 2005. Image Processing for the Analysis and Conservation of Paintings: Opportunities and Challenges. *Signal Processing Magazine, IEEE*, 22(5): 141–4.
- Berns, R.S., Byrns, S., Casadio, F., Fiedler, I., Gallagher, C., Imai, F.H., Newman, A. & Taplin, L.A. 2006. Rejuvenating the Color Palette of Georges Seurat's A Sunday on La Grande Jatte – 1884: A Simulation. *Color Research & Application*, 31(4): 278–93.
- Casadio, F., Miliani, C., Rosi, F., Romani, A., Anselmi, C., Brunetti, B., Sgamellotti, A., Andral, J.-L. & Gautier, G. 2013. Scientific Investigation of an Important Corpus of Picasso Paintings in Antibes: New Insights into Technique, Condition, and Chronological Sequence. *Journal of the American Institute for Conservation*, 52(3): 184–204.
- Gilot, F. & Lake, C. 1964. *Life with Picasso*. New York: McGraw-Hill.
- Giraudy, D. 1981–2. *L'œuvre de Picasso à Antibes*, 4 vols. Antibes: Musée Picasso/Château Grimaldi.
- Johnson, D.H., Erdmann, R.G. & Johnson, C.R. 2011a. Whole-painting Canvas Analysis using High- and Low-level Features. In: *IEEE 36th International Conference on Acoustics, Speech and Signal Processing (ICASSP)*. Piscataway, NJ: IEEE, pp. 969–72.
- Johnson, R., Johnson, D., Hamashima, N., Sung Yang, H. & Hendriks, E. 2011b. On the Utility of Spectral-Maximum-Based Automated Thread Counting from X-Radiographs of Paintings on Canvas. *Studies in Conservation*, 56(2): 104–14.
- Levin, A., Lischinski, D. & Weiss, Y. 2004. Colorization using Optimization. *ACM Transactions on Graphics*, 23(3): 689–94.
- Lowe, D.G. 1999. Object Recognition from Local Scale-invariant Features. In: *The Proceedings of the Seventh IEEE International Conference on Computer Vision*. Piscataway, NJ: IEEE, vol. 2, pp. 1150–7.
- MacDonald, L.W. 2006. *Digital Heritage: Applying Digital Imaging to Cultural Heritage*. Amsterdam; Boston: Elsevier.
- Markle, W. & Hunt, B. 1986. *Coloring a Black and White Signal using Motion Detection*. U. S. P. Office. USA: Colorization Inc. 4755870.
- Marty, P.F., Rayward, W.B. & Twidale, M.B. 2003. Museum Informatics. *Annual Review of Information Science and Technology*, 37: 259–94.
- Palma, G., Corsini, M., Cignoni, P., Scopigno, R. & Mudge, M. 2010. Dynamic Shading Enhancement for Reflectance Transformation Imaging. *Journal of Computing and Cultural Heritage*, 3(2): 1–20.
- Picasso, P. 2011. *Picasso Express*. Antibes: Musée Picasso.
- Saltelli, A., Ratto, M., Andres, T., Campolongo, F., Cariboni, J., Gatelli, D., Saisana, M. & Tarantola, S. 2008. *Global Sensitivity Analysis – The Primer*. Chichester: John Wiley & Sons.
- Sima, M. (photographs), de Staël, A. & Andral, J. L. (text) 2009. *L'atelier des combles*. Antibes, Musée Picasso & Paris: Hazan.
- Stanco, F., Battiato, S. & Gallo, G. eds. 2011. *Digital Imaging for Cultural Heritage Preservation: Analysis, Restoration, and Reconstruction of Ancient Artworks*. Digital Imaging and Computer Vision, CRC Press.
- Stork, D.G., Coddington, J. & Bentkowska-Kafel, A. eds. 2010. *Computer Vision and Image Analysis of Art*. Bellingham, WA: SPIE, Proceedings, vol. 7351.
- Styner, M., Brechbuhler, C., Szckely, G. & Gerig, G. 2000. Parametric Estimate of Intensity Inhomogeneities Applied to MRI. *Medical Imaging, IEEE Transactions*, 19(3): 153–65.
- Tsaftaris, S.A., Lister, K.H., Fiedler, I., Casadio, F. & Katsaggelos, A.K. 2011. Colorizing a Masterpiece [Applications Corner]. *Signal Processing Magazine, IEEE*, 28(3): 113–9.
- Vedaldi, A. & Fulkerson, B. 2008. VLFeat: An Open and Portable Library of Computer Vision Algorithms [accessed 5 February 2013]. Available at: <<http://www.vlfeat.org/>>