Article

Assessment of the Robustness of a Color Monitoring Chart Calibration Method for Crowdsourcing-Based Preventive Conservation

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Abstract: Monitoring environmental factors such as pollutants, relative humidity, light, etc. is needed to ensure a proper preventive conservation of cultural heritage. Since existing systems are expensive and difficult to maintain, we propose as a sustainable alternative the use of crowdsourced photographs taken by visitors using their cell phones. These images of a tailor made panel, including sensitive materials and a calibration color chart, are calibrated and colorimetric information extracted from them. The aim of this paper is assessing the robustness of the color chart and the calibration method used, and evaluating how the ageing of the materials of the chart can affect the accuracy of the calibration process. A choice is made between four candidate materials and a set of industrial inks. Several tests have been performed and mathematical metrics extracted, so the most suitable material is adequately selected. It has been checked how the image calibration process, employed for homogenizing information from the crowdsourced pictures, performs with real-life materials and colors to assess the possible degradation that may happen. This work is a part of a bigger project with the aim of building a crowdsourcing-based monitoring system for preventive conservation of cultural heritage.

Keywords: colorimetry; environmental monitoring; preventive conservation

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1. Introduction

All over the world, objects of historic and cultural values are exhibited and preserved in museum collections. To protect objects in collections from degradation they are held and exhibited in controlled environments, where ideally all ambient conditions are adjusted to minimize future damage to the heritage materials. This strategy, focused in preventing future deterioration acting on the potential causes of deterioration, is known as preventive conservation.

However, the perfect environment is impossible to achieve, and sometimes humidity, pollutants or lighting problems can reach a point where the material an exhibited cultural heritage item is made of starts suffering a quick degradation [1–3]. Sometimes harmful emissions come from inside. Building materials from furniture, showcases or panels, such as paints, woods or adhesives or cleaners, and even some objects from collections can emit gaseous pollutants. This problem is even more serious if the exhibited artifacts are stored in non-ventilated display [4,5].

Thus, even in the best conservation-suited environment, additional needs for surveillance of cultural heritage are likely to be required. In order to lighten human efforts on the task of surveillance, automatic monitoring resources are encouraged and proposed. These may take any mean for quantifying the possible decay, like sensing humidity or light or

checking the change in color of some material present when it is undergoing a degradation process [6].

One of the most evident signs of deterioration of heritage materials are color alterations. Color is probably the most significant property of cultural heritage objects. Not only in painting, but in sculpture and decorative arts color is carefully chosen, selecting materials, finishes and surface treatments. Aging of materials frequently produces color changes that can be related to degradation in different aspects and degrees of intensity. In some cases as in irreversible alterations of pigments and dyes it represents a major concern for conservators. Therefore, the availability of tools to monitor color change is of interest in cultural heritage conservation. At the same time, color change of certain reference materials can be used for indoor environment evaluation as a preventive conservation tool.

Colorimetric measurements are in fact frequently used for detecting degradation in different materials, using colorimeters or spectrophotometers [7,8]. The use of color change as an indicative of environmental changes has also been suggested [9,10]. Color monitoring is clearly relevant in the conservation field; it does not require complex equipment or specialized personnel, as a colorimeter is easy to operate. However, it is a time-consuming method, and has some application limitations on very irregular or delicate surfaces, as it requires contact.

Based on these premises, our research group has proposed a system for monitoring environmental conditions in museums based on the measurement of color changes by image processing. The objective of this system, besides being a low-cost preventive conservation tool, is to increase social awareness in relation to heritage conservation. For this purpose, the system uses crowdsourced pictures taken by visitors with their cell phones [11] (Figure 1). The usage of crowdsourcing techniques is acknowledged as a useful resource, which has been used for long in monitoring of biodiversity, astronomy, and other fields [12]. More recently has been proposed as a monitorization tool for cultural heritage preservation, using smartphone technologies [13–15].

Figure 1. Visual outline of the conceived cultural heritage conservation system by color monitoring via crowdsourcing.

Photographic cameras represent the acquired information analogously to the human visual system[16,17]. But, considering fabrication and physical component differences between models, images representing the same scene by disjoint cameras are likely to appear visually different to the same observer [18]. This is the main concern regarding the crowdsourced information, therefore a homogenisation via color calibration is needed to

perform an effective monitoring of the pieces. This requires the presence of a color chart when acquiring the content to be calibrated.

The mentioned approaches use mobile images individually adjusted using X-Rite charts as color reference. However, the X-Rite color chart has been designed provide bright colors for outdoor photography, and some of the tiles have too saturated colors [13], and its materials have not been tested to be compatible with heritage objects. Our monitoring system pretends a further step on these first approaches, designing and testing an optimized color chart, an accurate calibration method and developing an efficient color change detection system.

The previous stages of this project, the conception of the color chart, the verification of the suitability of the materials for the monitoring system, and an adaptive calibration algorithm for image processing have already been presented [11,19]. The color chart is mounted on an inert substrate together with several metal coupons used as sensitive materials.

This reference color chart has been specifically designed to cover all the range of the sRGB color space, which is shared by most phone cameras in usage. It is placed in the display case or exhibition space to be monitored in this project. Alongside the chart, metal coupons are placed. Possible inadequate environmental conditions that may affect the heritage artifacts will induce corrosion in the coupons. This corrosion process might take the form of a tarnishing, more or less uniform colored corrosion layers, or colored spots on the surface of the metal. These colorimetric cues are the relevant information to be extracted from the crowdsourced pictures, as warnings of unsuitable environmental conditions for the conservation of heritage assets.

The calibration process is one of the most critical parts of the monitoring system. Assuming most crowdsourced pictures are taken with different cameras, a quality calibration for every image is needed for homogenizing color information. According to this, the color chart needs to be consistent and stable enough to be used as a reliable reference for the color calibration algorithm.

So, the materials employed to build the display and chart and the coupons need to be carefully selected so they do not undergo possible strong chromatic deviations from the initial state; and they should not produce alterations in the metal coupons and, more important, in the heritage artifacts [11]. It is utmost important that the reference color chart remains unaffected so the quality of the picture calibration does not lower when deployed for a prolonged time. In addition, if by any reason the color references change, it is imperative to check how this change can affect the outcomes of the calibration process.

Thus, the aim of this paper is to evaluate robustness of the crowdsourced color evaluation system against environmental degradation of the reference display. The criterion adopted is mathematical robustness to discoloration. Since the main agent causing color modification in organic materials (including boards, papers and inks) is light, variations in the color chart on different materials due to exposure to UV radiation have been evaluated. For this purpose, periodic measurements of the exposed references have been carried out.

These measures are processed in different mathematical ways to evaluate the robustness of environmentally-induced color degradation in them. From this information, it is evaluated how possible light induced color variations may affect the accuracy of the calibration method.

Finally, conclusions are drawn and the selection of the most suitable material to build the crowdsourcing-based monitoring display are proposed.

2. Materials and Methods

2.1. Color Chart Design

The color chart has been conceived so the calibration to perform does not incur in unacceptable errors. It consists in 64 color patches of dimensions 1 cm × 1 cm arranged on 11 columns and 9 rows. There is a free space of 7 columns × 5 rows in the centre, where the metal coupons (or other references) can be placed (Figure 2).

The calibration process is performed by calculating a transfer function that projects the R, G and B information of each channel of the taken pictures into a reference space, where their corresponding coordinates take values that must be present in the calibrated image. Thus, all pictures after this operation should depict consistent color information [19], regardless of their camera of origin.

Figure 2. The reference color calibration chart, as it is conceived to be printed upon the materials under test.

With this conception in mind, the depicted colors present regularly sparse grey tones range in sRGB acting as valid as luminance values too, including maximum black and white, and the primaries red, green, blue, cyan, magenta and yellow. The remaining colors are combinations of equal shares of each RGB axis, and are furthermore designed to exist in the perceptual spaces as sRGB and inside CIELAB's boundary [19]. This avoids transformation errors when colors exist regardless of the color space to consider in further application. It is also assured that the possible range of values is covered equally, and inferring the projection of colors not present within the set of anchor colors not much accuracy is lost.

It is imperative that the manufactured color charts to be used in museum showcases are stable for a prolonged usage whilst maintaining the color characteristics mentioned above. This way they are expected to withstand the adverse ambient conditions that this project, in its global scope, is intended to monitor.

2.2. Color Chart Materials

Color charts have been printed by a graphic arts printer using selected materials for the support and UV resistant inks. Four candidate materials for the support have been evaluated: acid-free laminated paper, acid-free non-laminated paper, Forex Smart and Glasspack. The choice of these papers, within the options available on the market, has been based on the British Museum's Oddy Test database, to ensure their safety [20]. In addition, their light weight, firmness, low cost and ease of cutting and handling making it easy to build an exhibition structure with any of them, are suitable for the intended purpose.

The ink set tested for the color chart was LED-UV Xtreme Pro, by Deutsche Druckfarben. These inks are used for printing advertising posters intended for outdoor display, and they are known to resist solar radiation. Their lightfastness is rated 5 (yellow and magenta) and 8 (cyan and black) to blue wool standard according to the manufacturer [11].

The thickness of the ink has been measured using a Helios Digitrix II micrometer, with 1 μm resolution, by difference of the thickness of the blank paper and the printed

patches. The thickness strongly depends on the color, ranging from 2–3 μm in the lightest patches, up to 20–25 μm in the more saturated colors and 40 μm in the black patch.

2.3. Color Chart Evaluation

Therefore, a display structure is made from each one of the four support materials and the set of inks. Each test display has been exposed to a constant irradiation of UV light at 50 °C, using fluorescent UVA-340 lamps, following the ISO4892-3 standard in a Q-Lab QUV chamber [21].

Since the color charts are intended to be exposed in museum cases for a long time, the UV exposure time has been calculated to be equivalent to several museum years. Q-Lab QUV chamber lamps reproduce daylight conditions, which are equivalent to a 30,000 lux illuminance. As museum illuminance for non-sensitive materials is set at 300 lux, the illuminance in the chamber is (maximum) 100 times that in the museum. Thus, we can estimate that in the worst scenario (a non UV-filtered illumination), 144 h chamber exposure (six 24 h periods) can be approximated to 4 years of museum ($144 \text{ h} \times 100 = 14,400 \text{ h}$ of exposure / 10 h per day = 1440 days = 3.9 years).

Measures of the color coordinates have been taken for hours 0 (without degradation before exposure), 2, 4, 6, 24, 48, 72, 96, 120 and 144 using a Konica Minolta spectrophotometer CM-700-d, with 6 mm diameter mask, D65 as illuminant and at 10 degrees to the observer, in color space CIELAB. Every measure taken consists in an automatic average of three measurements on areas of 1 cm^2 . Its accuracy specifications reveal a repeatability tolerance of a standard deviation between 0 and 0.1% of the spectral reflectance, and within $0.04\Delta E_{ab}$ of the detected colorimetric value. As a representative set of colors of the printed charts to be evaluated, the patches corresponding to white, black, red, green, blue, cyan, magenta and yellow are taken. It is to be noted that the color patch corresponding to the white tone does not have any ink printed upon it, so it consists in the naked material. Therefore, the effect of the test on the substrate material can be tested when analysing the white patch. Consequently, the other color tones are considered indicators of the effect of the degrading ambiance on a combination of substrate and inks. Thus, the effect of the degrading ambiance on the naked substrate and on different mixtures of different amounts of inks can be observed, and its possible effects on the calibration process inferred.

The results are a list of progressive CIELAB coordinates along time for given color patches in every material combination. The CIE1976 $L^*a^*b^*$ color space, or CIELAB, is usually employed in heritage science matters as accurate color specification [22], while being uniform, device-independent and suitable for calculations such as calibrations [19].

Several means to describe the degradation have been considered. A graphical evolution along time of the CIELAB coordinates for the selected color patches has been observed (Figure 3). In addition, a good descriptor of degradation is a difference metric. The ΔE_{00} CIEDE2000 difference formula has been selected for this purpose, since it is designed to reflect CIELAB color differences according to human perception [23]. Equation (1) reflects its nature [24]. It defines a metric similar to a mathematical distance in the CIELAB color space, employing differences related to the physical lightness, chroma and hue (L , C and H). The S functions and parametric factors k define weights to the former quantities, and in order to improve its effectiveness for the blue range it employs an interactive term between C and H (R_T).

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T \left(\frac{\Delta C'}{k_C S_C}\right) \left(\frac{\Delta H'}{k_H S_H}\right)} \quad (1)$$

The difference formula has been employed to show a progressive degradation. Each CIELAB measure from each one of the time checkpoints is compared to the original zero-hour measurement, its difference calculated and its progress shown.

The analysis for the white, ink-free patch is particularly interesting for what it may reveal about the nature of degradation on the bare support material, without the ink acting as a cover. Special consideration has been given to measurements of CIELAB values and

differences concerning these patches. Their effect is measured by performing calibration processes using these degraded white values as reference, and the calibration error as CIEDE2000 difference is then evaluated for all materials.

Figure 3. Accumulative evolution of the CIEDE2000 difference for the white, black, cyan, magenta, yellow, red, green and blue patches along every measured point in time (2, 4, 6, 24, 48, 72, 96, 120, 144 h). The colors of the curves indicate the homologous patch, and the grey curve stands for the white one.

The next section will address the results, explaining the material to be chosen and which ones could be discarded or used as a temporary substitute. The choice ensures that the display will guarantee a stable calibration with consistent results, so the monitoring via crowdsourced images can be enabled for an extended period in a museum.

Aside, in order to demonstrate the capabilities of the conceived charts, an experiment that involves the calibration scheme outlined in [11,13] over pictures taken with commercial brands of phones has been performed. With the material chosen with the best results (explained in the following sections), a chart has been printed and photographed. Pictures have been taken with the following models: Xiaomi Mi10 lite 5G, Poco X3 NFC, Poco F3, Huawei P30, iPhone SE and Microsoft Surface Pro (Figure 4). This way, the crowdsourcing disparity is achieved. After having collected the pictures, the calibration process has been ran over them and the robustness evaluated. The calibrated color patches of each of the pictures have been compared with the reference color values in sRGB using the CIEDE2000 difference formula.

In addition to this, the mean digital CIELAB coordinates for every patch in each calibrated picture have been compared to the original spectrophotometer measurements so the accuracy of the calibrated values with respect to the original data can be assessed.

Figure 4. The six pictures from six different models of commercial cellphones that imitate the effects of image disparity by crowdsourcing.

3. Results and Discussion

The evolution of CIELAB coordinates of each of the considered color patches are listed in the Tables A1–A4. It should be noted that the white coordinate, corresponding to the ink-free spot of the color chart, undergoes a stronger variation in comparison to the other colors under study in all cases. This degradation, seen as a progressive shift of values, is especially remarkable in the b^* coordinate. This implies a process of yellowing, extremely pronounced for the Glasspack (Table A4). The inks act as a “shield” for the substrate material, given their greater stability and less intense degradation. The most stable of the materials considering its low variation is the acid-free laminated paper (Table A1).

Based on those tables, the CIEDE2000 differences for each one of the four materials under study are shown graphically (Figure 3). In general, the color patches with inks printed upon them show a relatively slow degrading, with a barely steep slate, staying in most cases under the ΔE_{00} CIEDE2000 < 1.5 threshold, implying a minimal perceivable color difference, only noticeable by trained eyes [25–27]. This indicates good stability and robustness in the considered exposition period.

Considering that materials such as papers usually are not as resistant towards chromatic deviation as other, more expensive materials like ceramics, it is promising to observe how small the induced error can be for the considered application.

It is interesting to note that on half of the tested materials, the color patches with only one ink printed (black, yellow, cyan or magenta) show a subtly stronger degradation than the other colors, which need more than one ink to be printed, following the additive YCMK system. This reinforces the idea of the nature of the inks as protective covers of the substrate material.

Therefore, the white ink-free patch shows a stronger degradation compared to the rest in the described graphs. Furthermore, its degradation can exceed a CIEDE2000 difference of value 3 for the acid-free paper and the Glasspack. It can be stated that the degradation of the ink-free spots is especially necessary to consider for the whole experiment (Figure 5), since an excessive difference with the zero-hour original value may lead to an erroneous color calibration process. This fact could compromise the whole monitoring mechanism.

Figure 5. Accumulative evolution of the CIEDE2000 difference for the white patches along every measured point in time (2, 4, 6, 24, 48, 72, 96, 120, 144 h). Red: Acid-Free Laminated Paper; Blue: Acid-Free Paper; Green: Forex Smart; Black: Glasspack.

Therefore, a deeper observation of the white spot for all the considered materials has been done. Several “dummy” color charts have been generated. The colored spots have been conserved, but the value corresponding to white patch has been substituted in each one of the materials with the RGB color coordinates corresponding to the CIELAB of every taken measure for the given time checkpoints. This is done for all four substrates. Then, the calibration process as described in [19] has been run on each of them with respect to the corresponding zero-hour color chart as the reference. Thus, the drifting effect of the decoloring towards the yellow of the white spot on the whole calibration process can be measured.

The subjects of calibration have been seven color stripes, in order to assess its effect on a variety of surfaces. Four of them represent silver and copper extracted textures from other photographs, since the indicator material coupons for the monitoring system are will be made of both metals. The three others represent a neutral grey hue (RGB = 128, 128, 128), a uniform copper color (RGB = 199, 140, 98) and a bright yellow (RGB = 255, 230, 128). They are used to see the effects of calibration with an erroneous white reference on different zones of the color space: the center, the region of copper tones, considering silver will mainly engulf luminance-predominant hues, and the yellow stripe represents the yellowing shown by aged whites (Figure 6). After each process, the stripes are extracted and their mean CIELAB coordinates and CIEDE2000 difference calculated. Results are presented in Tables 1–4.

For the time interval considered the calibrations of the modified color charts present a moderate difference, all values remaining in a close range even between the least and most deteriorated state, in every case smaller than the acceptability threshold of CIEDE2000. The most stable material is the acid-free paper (Table 1), that undergoes practically no deviation, whilst the others still fluctuate, even if slightly. Nevertheless, the acid-free non-laminated paper presents the best balance on lower mean error (lower than the acid-free paper) with acceptable variation (Table 2).

Figure 6. The “dummy” colors and textures conceived for evaluating the color calibration procedure with degraded white patches.

Table 1. CIEDE2000 differences for the seven tested calibrated color stripes for the acid free paper.

Hour	Stripe 1	Stripe 2	Stripe 3	Stripe 4	Stripe 5	Stripe 6	Stripe 7
2 h	1.017	0.594	0.0	1.787	0.896	0.022	0.047
4 h	1.017	0.594	0.0	1.787	0.896	0.022	0.047
6 h	1.017	0.594	0.0	1.787	0.896	0.022	0.047
24 h	1.017	0.594	0.0	1.787	0.896	0.022	0.047
48 h	1.017	0.594	0.0	1.787	0.896	0.022	0.047
72 h	1.017	0.594	0.0	1.787	0.896	0.022	0.047
96 h	1.072	0.595	0.0	1.779	0.851	0.022	0.047
120 h	1.072	0.595	0.0	1.779	0.851	0.022	0.047
144 h	1.072	0.595	0.0	1.779	0.851	0.0225	0.047
Mean	1.035	0.594	0.0	1.784	0.881	0.022	0.0
Variance	0.001	0.0	0.0	0.0	0.0	0.0	0.0

Table 2. CIEDE2000 differences for the seven tested calibrated color stripes for the acid free laminated paper.

Hour	Stripe 1	Stripe 2	Stripe 3	Stripe 4	Stripe 5	Stripe 6	Stripe 7
2 h	1.108	0.712	0.949	1.241	0.950	0.0	0.0
4 h	0.155	0.077	0.0	0.073	0.153	0.0	0.0
6 h	0.156	0.077	0.0	0.073	0.15	0.0	0.0
24 h	0.117	0.090	0.0	0.101	0.20	0.0	0.0
48 h	0.332	0.099	0.0	1.66	0.53	0.0	0.0
72 h	0.358	0.086	0.0	1.66	0.51	0.0	0.0
96 h	0.358	0.086	0.0	1.66	0.51	0.0	0.0
120 h	1.021	0.588	0.0	1.77	0.890	0.0225	0.0453
144 h	0.358	0.086	0.0	1.66	0.51	0.0	0.0
Mean	0.44	0.211	0.105	1.1	0.49	0.003	0.005
Variance	0.121	0.056	0.089	0.535	0.076	0.0	0.0

Table 3. CIEDE2000 differences for the seven tested calibrated color stripes for the Glasspack.

Hour	Stripe 1	Stripe 2	Stripe 3	Stripe 4	Stripe 5	Stripe 6	Stripe 7
2 h	0.356	0.086	0.0	1.662	0.510	0.0	0.0
4 h	0.356	0.086	0.0	1.662	0.510	0.0	0.0
6 h	1.033	0.595	0.0	1.777	0.881	0.023	0.045
24 h	1.021	0.570	0.949	1.781	0.891	0.023	0.045
48 h	0.355	0.0865	0.0	1.662	0.510	0.0	0.0
72 h	1.033	0.595	0.0	1.777	0.881	0.022	0.045
96 h	1.037	0.595	0.0	1.777	0.881	0.023	0.045
120 h	1.112	0.888	0.273	2.156	1.967	1.217	1.438
144 h	0.391	0.0865	0.0	1.661	0.510	0.0	0.0
Mean	0.744	0.399	0.136	1.768	0.838	0.145	0.18
Variance	0.116	0.086	0.09	0.022	0.19	0.144	0.198

Table 4. CIEDE2000 differences for the seven tested calibrated color stripes for the Forex Smart.

Hour	Stripe 1	Stripe 2	Stripe 3	Stripe 4	Stripe 5	Stripe 6	Stripe 7
2 h	0.356	0.0864	0.0	1.662	0.510	0.0	0.0
4 h	0.356	0.086	0.0	1.662	0.510	0.0	0.0
6 h	0.161	0.077	0.0	0.074	0.153	0.0	0.0
24 h	1.032	0.594	0.0	1.776	0.881	0.023	0.045
48 h	1.122	0.633	0.247	2.141	1.156	0.587	1.132
72 h	1.110	0.888	0.272	2.156	1.966	1.216	1.438
96 h	0.161	0.0771	0.0	0.073	0.153	0.0	0.0
120 h	0.122	0.0901	0.0	0.101	0.203	0.0	0.0
144 h	1.123	0.890	0.272	2.150	1.959	1.216	1.438
Mean	0.616	0.380	0.088	1.311	0.832	0.338	0.450
Variance	0.191	0.119	0.015	0.788	0.465	0.253	0.399

However, it is interesting to note that the differences shown in the Tables 1–4 are not continuous, but they fluctuate at each time step. A reason for this can be understood when the “white” values for every paper are represented in their 3D color space (Figures A1–A5) and their evolution along time observed. The white tones, represented by dots in space, do not follow a linear evolution over time, but evidently fluctuate in space when under the chromatic deviation process, following an irregular evolution from the initial white tone in different directions during each time step. This is represented using arrows, as seen in the figures. For every paper, the arrows in the a^*L^* , b^*L^* and a^*b^* planes (Figures A1–A4), and in the whole $L^*a^*b^*$ space (Figure A5) are represented. Depending on the position in space of any affected color during the calibration process, its distance from its projected reference value will be of different magnitude and orientation depending on its initial position, closer or farther away from the state of the white value in the chart in the moment the calibration is performed. This is extensible to any other reference color in the chart. This irregular variability of the reference color depending on degradation and time explains the fluctuating results when calibrating.

Aside of that, it is also remarkable to see how, even when performing a calibration with deteriorated color charts, the results presented here are of a higher quality than other similarly oriented cultural heritage conservation works with ideal charts [14]. Whilst state-of art accepted CIEDE2000 differences exceed the minimal perceivable difference threshold with an ideal chart, our physically printed charts on every material among the tested ones under a chromatic deviation equivalent to 4 years still depict values inferior to

the threshold in all the cases, and most of them with a CIEDE2000 value between 0 and 1 after application of the calibration process.

Overall, concluding from the color difference values, it can be observed that the four materials under consideration (laminated acid-free paper, acid-free paper, Forex Smart and Glasspack) are robust enough to resist the effects of chromatic degradation over a long period without incurring in errors noticeable to the human eye in the calibration process, in spite of the material degradation that still occurs, even if slight, when observing the metrics. If the selection of the material would only depend on the mathematical chromatic stability criterion, the most suitable and balanced one would be the acid-free laminated paper. Even if the differences are subtle from a numerical perspective, Glasspack would be discarded, and acid-free paper and Forex Smart would be seen as the second and third choices, respectively.

Out of the performed tests, when it comes to deploying the structures, the selected materials should fulfil some basic requirements in order to be used in a museum environment. The most important one is that the material should be innocuous to the heritage assets in its environment. Many materials are known to release different pollutants that can cause degradation of sensitive materials [5,28]. Additionally, since the chart is to be used in combination with metallic coupons (acting as sensitive materials for the environment), the materials of the chart should also be interred to the metal coupons. In order to check these aspects, the four candidate materials have been subject to the Oddy Test. Based on these results, which can be found in detail in a related work by the authors [11], acid-free laminated paper has been chosen, considering the balance between color stability and emission of harmful pollutants.

Thus, considering the facts above, the most suitable material for building the calibration display has been the acid-free laminated paper. Its chromatic stability is the best ones among all the tests, whilst fulfilling the real-life safety requirement. The calibration process for the crowdsourced images can be therefore considered as safe to perform for a prolonged time.

Having decided the definitive materials for building the charts, one has been printed to evaluate its suitability to endure the disparity effects on crowdsourced imaging. Six pictures with different phones, as outlined in the previous section, have been taken in the lab and the CIEDE2000 differences for each color patch extracted. Also, the standard deviation for all the metrics corresponding to the same patch has been calculated (Table A5).

As seen there, not only the quality metrics are excellent, but also the standard deviation is close to 0, meaning the color calibration is adequately performed on every picture and there is an extremely low variability between the processed images, regardless of their camera of source.

In Tables A6 and A7 the accuracy of the calibration scheme thanks to the robustness of the chart is demonstrated. The average digital L^* , a^* and b^* coordinates for the color patches of each calibrated picture have been extracted and compared with measurements from the printed chart made with the spectrophotometer. Their extreme similarity in all cases reveal the good performance of the calibration scheme, which is allowed with the robust printing on the chart.

4. Conclusions

The work described above has made it possible to evaluate the performance of the developed calibration system in a non-ideal context and to assess how well it works. The application of the calibration method on four different materials has allowed to evaluate the influence of the ageing of different materials in the outcomes of the calibration of the images. Mathematical criteria have been taken in order to select the most adequate support material to build the structure. Under an analysis of color mathematics over the test results, very mild differences have been found between the four of them. Robustness to externally-induced chromatic deviation is practically analogue in every studied case, with a revealed decay that is non-noticeable by human eye.

Thus, the calibration process allows to extract valid information from any taken images, guaranteeing that no errors originating from the color change of the reference charts may hinder the proper operation of the entire system.

Finally, the results support the possibility of manufacturing customized reference color charts using low-cost commercial materials, as the developed calibration process can easily overcome the small color drift introduced by aging. These reference color charts can be used to design low-cost conservation tools, affordable for small museums with limited budget.

5. Future Steps

Considering that the work presented in this paper is engulfed in a the framework of a bigger project, further steps to consider from this point on are the natural continuations of the premises exposed in the previous sections.

The calibration of crowdsourced images, to obtain reliable color coordinates from RGB images obtained with different cameras is a challenging question. Although the same accuracy of a dedicated instrument (spectrophotometer) can not be expected, results shown in this and previous papers by the authors [11–15,19] and other colleagues [13–15] show promising results of this approach for our intended application (detection of degradation of heritage artifacts).

After these initial tests, deployment of the color charts in real locations is currently under way. Charts have been industrially printed, and with the corresponding metal coupons, they have been installed in museums, where they are being tested during an one-year period. Their performance and robustness will be evaluated, and possible improvements of the calibration and the crowdsourcing system will be made during that time.

Calibration of crowdsourced images, from different cameras and acquired under non-ideal illumination conditions and angles, is a challenging question that will be addressed in this step. While the accuracy of a dedicated instrument (spectrophotometer or calibrated professional camera) can no be expected, preliminary results suggest that can be enough to detect color changes in the sensitive materials, thus serving as alert system of environmental conditions dangerous for the conservation of heritage artifacts.

When a good performance can be assessed, the whole system can be officially launched and installed.

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Appendix A

Table A1. L*a*b* coordinate value evolution for the acid-free laminated paper.

L*a*b* (10°/D65) for Black				L*a*b* (10°/D65) for Red			L*a*b* (10°/D65) for Green			L*a*b* (10°/D65) for Cyan		
Hour	L*	a*	b*	L*	a*	b*	L*	a*	b*	L*	a*	b*
0 h	30.34	−0.15	−1.29	55.80	47.92	37.98	62.11	−41.26	33.67	69.35	−33.79	−13.69
2 h	28.25	−0.47	−1.16	55.85	48.41	39.36	62.04	−41.25	33.95	69.00	−34.12	−14.09
4 h	28.48	−0.48	−1.01	55.80	48.25	38.87	61.98	−40.78	34.13	68.98	−34.16	−13.59
6 h	28.32	−0.48	−1.12	55.77	48.24	39.06	61.92	−40.90	33.80	69.06	−34.10	−13.86
24 h	28.20	−0.53	−1.16	55.79	48.11	38.99	61.87	−40.87	33.76	69.03	−34.10	−12.94
48 h	28.29	−0.45	−1.15	55.74	48.07	38.80	61.80	−40.92	33.45	69.09	−34.00	−13.25
72 h	28.27	−0.48	−1.20	55.80	47.92	38.98	61.85	−40.52	33.29	69.10	−33.89	−13.26
96 h	28.32	−0.42	−1.22	55.78	47.82	38.66	61.87	−40.42	33.26	69.08	−33.89	−13.3
120 h	28.54	−0.48	−1.18	55.84	47.57	38.42	61.8	−40.01	32.81	69.1	−33.76	−13.46
144 h	28.58	−0.41	−1.25	55.87	47.36	38.14	61.84	−39.84	32.71	69.27	−33.51	−13.36
L*a*b* (10°/D65) for White				L*a*b* (10°/D65) for Blue			L*a*b* (10°/D65) for Yellow			L*a*b* (10°/D65) for Magenta		
Hour	L*	a*	b*	L*	a*	b*	L*	a*	b*	L*	a*	b*
0 h	92.30	−0.36	−1.19	49.00	−17.13	−30.55	84.55	−6.94	77.08	56.47	54.51	0.50
2 h	92.09	−0.36	−0.66	48.98	−18.15	−29.87	84.38	−6.51	77.17	56.58	55.14	1.34
4 h	92.00	−0.41	−0.19	48.96	−18.03	−29.71	84.38	−6.24	76.80	56.55	54.95	1.04
6 h	92.09	−0.50	0.05	48.93	−17.96	−30.05	84.30	−6.27	76.79	56.58	54.86	1.15
24 h	92.04	−0.78	1.34	48.86	−18.06	−29.92	84.33	−6.04	76.74	56.63	54.86	1.23
48 h	92.03	−0.86	1.62	49.00	−18.17	−29.77	84.27	−6.15	76.42	56.61	54.75	1.08
72 h	92.09	−0.87	1.66	48.82	−17.96	−29.81	84.22	−6.06	76.10	56.64	54.79	1.10
96 h	92.22	−0.9	1.77	49	−18.3	−29.68	84.16	−5.98	75.93	56.58	54.75	1.19
120 h	92.1	−0.9	2.16	49.08	−18.17	−29.24	84.04	−5.84	75	56.64	54.32	1.13
144 h	92.21	−0.9	2.1	49.07	−18.21	−29.08	84.07	−5.89	74.63	56.6	54.27	1.12

Table A2. L*a*b* coordinate value evolution for the acid-free paper.

L*a*b* (10°/D65) for black				L*a*b* (10°/D65) for Red			L*a*b* (10°/D65) for Green			L*a*b* (10°/D65) for Cyan		
Hour	L*	a*	b*	L*	a*	b*	L*	a*	b*	L*	a*	b*
0 h	29.84	1.31	−1.37	57.46	47.89	39.86	64.07	−40.32	35.10	71.59	−31.00	−16.15
2 h	30.11	1.37	−1.12	57.65	48.27	39.91	64.15	−39.21	34.72	71.29	−31.08	−15.63
4 h	30.14	1.28	−1.11	57.39	48.11	39.66	63.83	−39.14	34.81	71.20	−31.17	−14.99
6 h	29.99	1.42	−1.12	57.50	48.03	39.80	63.79	−39.21	34.43	71.11	−31.20	−14.86
24 h	30.59	1.43	−0.93	57.49	47.72	39.56	63.60	−38.61	34.60	71.03	−31.23	−13.83
48 h	30.31	1.56	−0.87	57.45	47.59	39.14	63.63	−38.37	33.84	71.05	−31.08	−13.30
72 h	30.07	1.65	−0.84	57.42	47.57	39.27	63.62	−38.08	33.83	70.92	−31.02	−13.04
96 h	30.42	1.61	−0.7	57.4	47.32	39.01	63.56	−37.81	33.55	71.06	−30.72	−12.6
120 h	30.53	1.67	−0.69	57.51	46.79	38.72	63.66	−37.41	33.29	71.1	−30.6	−12.17
144 h	30.57	1.73	−0.66	57.41	46.96	38.64	63.6	−37.27	33.02	71.2	−30.28	−12.32

Table A2. Cont.

Hour	L*a*b* (10°/D65) for White			L*a*b* (10°/D65) for Blue			L*a*b* (10°/D65) for Yellow			L*a*b* (10°/D65) for Magenta		
	L*	a*	b*	L*	a*	b*	L*	a*	b*	L*	a*	b*
0 h	95.57	0.07	−0.93	50.98	−17.55	−33.05	87.11	−6.26	79.80	58.19	55.42	−0.71
2 h	95.34	−0.18	0.64	50.69	−17.58	−32.24	86.84	−5.79	78.90	58.44	55.28	0.35
4 h	95.21	−0.21	1.24	50.52	−17.50	−31.82	86.59	−5.32	79.06	58.25	55.26	0.39
6 h	95.13	−0.30	1.69	50.55	−17.58	−31.73	86.53	−5.33	78.68	58.33	55.01	0.74
24 h	94.89	−0.54	3.27	50.56	−17.49	−30.88	86.38	−4.82	78.30	58.34	54.60	1.16
48 h	94.66	−0.55	3.80	50.48	−17.53	−30.35	85.89	−4.73	77.32	58.27	54.24	1.63
72 h	94.83	−0.48	3.61	50.56	−17.83	−29.92	86.01	−4.67	76.63	58.43	54.01	1.90
96 h	94.91	−0.4	3.48	50.46	−17.47	−29.47	85.9	−4.34	76.33	58.39	53.8	2.03
120 h	94.95	−0.37	3.33	50.55	−17.45	−29.17	85.77	−4.27	75.05	58.47	53.38	2.11
144 h	94.99	−0.3	3.02	50.66	−17.62	−28.86	85.77	−4.1	74.66	58.4	53.34	1.87

Table A3. L*a*b* coordinate value evolution for the Forex Smart.

Hour	L*a*b* (10°/D65) for Black			L*a*b* (10°/D65) for Red			L*a*b* (10°/D65) for Green			L*a*b* (10°/D65) for Cyan		
	L*	a*	b*	L*	a*	b*	L*	a*	b*	L*	a*	b*
0 h	28.34	1.10	−1.79	55.15	47.09	38.80	62.03	−41.57	35.46	69.08	−32.53	−11.65
2 h	28.36	1.07	−1.72	55.55	47.29	39.14	61.76	−41.01	35.07	69.10	−32.22	−11.28
4 h	28.42	1.11	−1.74	55.37	47.27	38.93	61.79	−40.75	35.07	69.07	−32.01	−11.51
6 h	28.50	1.26	−1.66	55.39	47.08	38.83	61.66	−40.54	34.92	68.79	−31.96	−10.72
24 h	28.65	1.31	−1.45	55.29	46.85	38.60	61.69	−39.97	34.75	68.95	−31.69	−11.11
48 h	28.85	1.63	−1.36	55.31	46.58	38.21	61.56	−39.71	34.08	69.03	−31.26	−10.88
72 h	28.88	1.72	−1.36	55.36	46.40	37.96	61.54	−39.41	33.82	69.01	−30.91	−10.63
96 h	29.04	1.83	−1.27	55.3	46.25	37.79	61.57	−38.93	33.32	68.99	−30.85	−10.87
120 h	28.94	1.85	−1.18	55.44	46	37.59	61.51	−38.88	33.06	69.04	−30.8	−10.55
144 h	29.05	1.99	−1.12	55.4	45.84	37.36	61.62	−38.57	33.14	69.12	−30.59	−10.73
Hour	L*a*b* (10°/D65) for White			L*a*b* (10°/D65) for Blue			L*a*b* (10°/D65) for Yellow			L*a*b* (10°/D65) for Magenta		
	L*	a*	b*	L*	a*	b*	L*	a*	b*	L*	a*	b*
0 h	91.21	−0.91	2.13	48.76	−18.95	−30.34	83.86	−7.18	77.30	56.00	53.65	−0.05
2 h	91.41	−0.81	2.41	48.40	−18.67	−29.49	83.87	−6.56	76.88	56.41	53.83	0.87
4 h	91.38	−0.77	2.31	48.59	−18.93	−29.17	83.70	−6.33	76.52	56.29	53.67	1.24
6 h	91.39	−0.76	2.25	48.58	−18.89	−29.11	83.67	−6.05	76.16	56.27	53.57	1.04
24 h	91.42	−0.69	2.19	48.37	−18.34	−28.52	83.47	−5.74	75.29	56.35	52.99	1.07
48 h	91.20	−0.72	2.18	48.69	−18.47	−28.47	83.16	−5.65	74.51	56.40	52.82	0.85
72 h	91.20	−0.65	2.64	48.79	−18.00	−28.26	83.03	−5.49	73.81	56.55	52.55	0.99
96 h	91.02	−0.64	3.2	48.67	−18.01	−27.58	82.91	−5.13	73.43	56.52	52.27	1.16
120 h	91.1	−0.68	3	48.8	−17.73	−27.33	82.52	−4.85	72.43	56.51	51.98	1.42
144 h	90.85	−0.66	3.81	48.99	−17.84	−27.19	82.63	−4.75	72.15	56.49	51.89	1.14

Table A4. L*a*b* coordinate value evolution for the Glasspack.

L*a*b* (10°/D65) for Black				L*a*b* (10°/D65) for Red			L*a*b* (10°/D65) for Green			L*a*b* (10°/D65) for Cyan		
Hour	L*	a*	b*	L*	a*	b*	L*	a*	b*	L*	a*	b*
0 h	29.22	1.13	−1.39	55.86	46.31	38.82	62.48	−41.28	34.08	71.01	−27.50	−16.45
2 h	29.64	1.14	−1.22	56.00	46.16	38.11	62.37	−40.45	33.66	70.95	−27.15	−16.35
4 h	29.56	1.19	−1.20	55.92	45.97	38.10	62.28	−40.16	33.59	70.98	−26.92	−15.94
6 h	29.62	1.20	−1.14	55.84	46.18	38.04	62.30	−39.98	33.58	70.99	−27.09	−15.99
24 h	29.75	1.31	−0.99	55.91	45.63	37.69	62.19	−39.29	33.03	70.59	−27.77	−15.62
48 h	29.74	1.34	−0.95	55.80	45.52	37.43	62.16	−38.92	32.69	70.75	−27.25	−14.30
72 h	29.90	1.45	−0.82	55.88	45.29	37.14	62.09	−38.82	32.49	70.37	−27.33	−13.54
96 h	29.79	1.52	−0.76	55.9	45.15	37.1	62.08	−38.77	32.62	70.19	−27.57	−12.84
120 h	30.01	1.56	−0.71	55.84	45.03	36.96	62.06	−38.5	32.21	70.35	−27.14	−12.07
144 h	30.07	1.64	−0.66	55.78	44.87	36.62	61.97	−38.04	32.17	69.83	−27.5	−11.14
L*a*b* (10°/D65) for White				L*a*b* (10°/D65) for Blue			L*a*b* (10°/D65) for Yellow			L*a*b* (10°/D65) for Magenta		
Hour	L*	a*	b*	L*	a*	b*	L*	a*	b*	L*	a*	b*
0 h	92.83	−0.13	−3.32	49.20	−16.42	−33.92	85.05	−7.65	77.85	56.39	54.23	−1.82
2 h	92.70	−0.04	−3.30	49.27	−16.38	−33.29	84.81	−7.04	77.53	56.53	54.67	−1.28
4 h	92.69	−0.05	−3.21	49.29	−16.45	−32.94	84.59	−6.76	76.98	56.72	54.05	−1.14
6 h	92.69	−0.07	−3.19	49.23	−16.36	−32.88	84.61	−6.55	77.11	56.59	54.27	−1.01
24 h	92.51	−0.28	−2.14	49.27	−16.68	−31.75	84.21	−6.14	76.25	56.65	53.79	−0.88
48 h	91.85	−0.75	0.45	49.14	−16.54	−31.31	83.99	−6.08	75.39	56.68	53.39	−0.72
72 h	91.01	−1.00	4.48	49.25	−16.57	−30.87	83.81	−5.71	74.91	56.72	53.03	−0.38
96 h	90.5	−1.08	6.73	49.32	−16.69	−30.7	83.58	−5.52	74.44	56.7	52.83	−0.33
120 h	90.32	−1.09	7.79	49.45	−16.53	−30.4	83.56	−5.27	74.16	56.71	52.43	0.09
144 h	89.54	−0.92	9.99	49.42	−16.64	−29.8	83.32	−4.8	73.86	56.68	52.26	0.32

Table A5. Accuracy CIEDE2000 ΔE metrics of the 64 color patches for the six calibrated pictures of different phone camera. The last column describes the standard deviation of all measures for the same patch.

Patch	Phone 1	Phone 2	Phone 3	Phone 4	Phone 5	Phone 6	Std
0	0.271929435	0.250142483	0.221759991	0.102924129	0.333997652	0.02889376	0.113844225
1	0.246394516	0.276568278	0.303733855	0.229285331	0.184830909	0.2585082	0.040876939
2	0.128665273	0.204957469	0.314525605	0.231916135	0.137999458	0.313871559	0.081434158
3	0.483161542	0.213342092	0.618528678	0.392071387	0.280235419	0.27769858	0.152210414
4	0.313248179	0.284205884	0.245130203	0.379021543	0.24192656	0.173508225	0.070180908
5	0.188959223	0.171871706	0.100481345	0.367691911	0.195481226	0.25228767	0.090232708
6	0.110569298	0.18901037	0.188615355	0.274788313	0.241280289	0.070489034	0.077076837
7	0.250987053	0.152319178	0.093222269	0.09258494	0.142928146	0.185631334	0.05998585
8	0.253062422	0.159611492	0.355350867	0.287696462	0.262338893	0.176692455	0.072416772
9	0.268234629	0.10624681	0.267494498	0.164670277	0.299191508	0.223860972	0.073285739
10	0.494465483	0.274353047	0.416477788	0.252188337	0.600899356	0.441961764	0.132571583
11	0.494430709	0.139650227	0.48584779	0.271046396	0.314133958	0.236939292	0.141213687

Table A5. Cont.

Patch	Phone 1	Phone 2	Phone 3	Phone 4	Phone 5	Phone 6	Std
12	0.314748289	0.230974566	0.184904178	0.145349096	0.185299813	0.102617279	0.073243983
13	0.409152503	0.75173015	0.137526243	0.060919873	0.199753181	0.131034981	0.259275007
14	0.263351538	0.211111325	0.196702758	0.245021707	0.164199032	0.263634505	0.040121722
15	0.304366455	0.207033376	0.054902258	0.217543358	0.276406465	0.205527194	0.086545131
16	0.236335827	0.222221341	0.306217465	0.104679479	0.268579199	0.318121364	0.077333208
17	0.237967542	0.265062979	0.301860365	0.073160295	0.192150012	0.22098815	0.079062986
18	0.110320337	0.594209319	0.201147895	0.394128154	0.33643895	0.124944712	0.18595185
19	0.099399921	0.241221618	0.350330214	0.324005545	0.053144767	0.186854282	0.119190645
20	0.181989329	0.238946561	0.169368853	0.190502742	0.295535589	0.257431247	0.049623555
21	0.2580484	0.382669565	0.283228092	0.161051904	0.181045483	0.208221277	0.081328547
22	0.214421129	0.110443083	0.140606524	0.275791862	0.091649353	0.140983478	0.069573943
23	0.450805286	0.209319213	0.411224745	0.151647883	0.168650534	0.079854552	0.150383577
24	0.171222872	0.226234714	0.188879191	0.194980934	0.199155444	0.207279831	0.018406291
25	0.152289768	0.256837556	0.307190318	0.346386874	0.127140971	0.08185859	0.106615734
26	0.356644033	0.061838464	0.219770463	0.270739179	0.354349674	0.263414879	0.10869328
27	0.187593087	0.211199491	0.214494541	0.169110386	0.2823889	0.28511742	0.048438277
28	0.356117452	0.505335328	0.389270889	0.338597579	0.40667726	0.335241222	0.063807319
29	0.325845986	0.283256129	0.232253968	0.180118952	0.373804323	0.171327938	0.081036101
30	0.257721684	0.073532058	0.299460614	0.267266773	0.120704256	0.305078435	0.09850842
31	0.204883882	0.249043347	0.150790974	0.299462136	0.26690004	0.127182187	0.067693635
32	0.354744452	0.118531967	0.211344119	0.117260901	0.165009622	0.171754839	0.088263312
33	0.138475897	0.260654569	0.210827597	0.220642381	0.223974272	0.189015626	0.040954298
34	0.140417367	0.257450543	0.134716096	0.17360391	0.169367903	0.208210855	0.045963991
35	0.232165205	0.521510048	0.351764324	0.235658347	0.378368252	0.334991002	0.106829021
36	0.218653655	0.214866192	0.23913092	0.185065996	0.247875457	0.118472856	0.047255538
37	0.305974416	0.179246924	0.339730226	0.200745372	0.160504642	0.233818131	0.071863476
38	0.060738709	0.055084875	0.195714181	0.220931635	0.128891128	0.19233017	0.072079879
39	0.379547586	0.415247839	0.391157571	0.128574633	0.237143754	0.170774169	0.124059676
40	0.334211135	0.123229265	0.484157906	0.160156494	0.29890712	0.35468809	0.133077681
41	0.370134132	0.137457002	0.392479982	0.234040247	0.44610453	0.281622243	0.114270914
42	0.492072262	0.247497877	0.363951702	0.525324505	0.403115261	0.25598056	0.116102014
43	0.421817046	0.236502276	0.310510172	0.239484894	0.220192922	0.15967778	0.090802861
44	0.22089895	0.157628951	0.270259166	0.20894853	0.155598179	0.217501717	0.043284776
45	0.290053218	0.12739633	0.176708403	0.177355072	0.186791632	0.212106174	0.05405787
46	0.236755082	0.369918654	0.20643606	0.278181682	0.185716963	0.106199396	0.08920253
47	0.275106993	0.232808008	0.075272426	0.209816723	0.207441311	0.199562965	0.066972122
48	0.224351759	0.10834236	0.157863641	0.199064517	0.153471324	0.05578121	0.061027414
49	0.16280386	0.347327304	0.190986044	0.237372587	0.221982283	0.320376686	0.072656193
50	0.147493647	0.218578621	0.145495864	0.119924133	0.224250937	0.168345985	0.042231686

Table A5. Cont.

Patch	Phone 1	Phone 2	Phone 3	Phone 4	Phone 5	Phone 6	Std
51	0.366139272	0.407310318	0.137487369	0.289239354	0.26112567	0.202729769	0.100307067
52	0.191806358	0.210480308	0.132550063	0.191274056	0.231185692	0.244145522	0.039303019
53	0.409009143	0.219582643	0.353465585	0.176858914	0.186257238	0.107491126	0.115119371
54	0.307635426	0.191899847	0.180955372	0.113646121	0.20697474	0.246631571	0.065290027
55	0.348954311	0.124675535	0.259566851	0.123555133	0.207567451	0.195613019	0.085710039
56	0.213574169	0.178364648	0.08206161	0.198903095	0.214846324	0.18656758	0.049661196
57	0.372069484	0.160653578	0.148216046	0.147258129	0.196601652	0.011783546	0.116280205
58	0.214738005	0.296587276	0.156198431	0.188951579	0.332348454	0.125395066	0.080615932
59	0.243485091	0.130124137	0.137554049	0.13029295	0.257885155	0.191018401	0.058240919
60	0.025819775	0.205919013	0.171627421	0.170378196	0.155762861	0.185552155	0.064327365
61	0.367164346	0.087332255	0.224571641	0.349241976	0.178035342	0.081899237	0.123812157
62	0.20323023	0.186293009	0.341428577	0.273541377	0.033248662	0.134440897	0.107316104
63	0.275532624	0.076531235	0.231020993	0.420800578	0.225614503	0.501730541	0.151873651

Table A6. Average digital L*, a* and b* coordinate values for each one of the 64 color patches in the calibrated images 1, 2 and 3, compared to average spectrophotometer values taken from the original printed chart.

Patch	Image 1			Image 2			Image 3			Original		
	L*	a*	b*	L*	a*	b*	L*	a*	b*	L*	a*	b*
0	27.52896076	1.940085385	−2.46434117	27.5911044	1.684838075	−2.187704511	27.26781324	1.840957936	−2.393766221	28.48	1.76	−1.79
1	30.52844788	3.425624636	−16.63516294	30.39432245	3.77587721	−17.15388393	30.89045132	3.388856611	−16.70397288	31.275	3.41	−16.695
2	37.11333236	5.501754653	−36.03067571	36.92291348	5.439984149	−36.04881916	36.68027531	5.676916174	−36.29706034	37.21	5.7	−36.18
3	44.85144292	1.055814781	−39.6303457	44.49874378	1.412425833	−39.95825878	44.11143412	1.512465575	−40.53197996	43.535	1.555	−40.78
4	37.55780127	−24.03463716	7.061906094	37.82659385	−23.89571759	7.583611232	37.35753996	−23.8432244	6.906667172	38.09	−25.245	7.95
5	39.15102941	−23.26824399	−7.282216276	39.01746451	−23.39561091	−7.298362757	39.69673034	−23.63061994	−7.206427581	39.515	−23.895	−7.49
6	44.19535371	−3.540097313	−39.41698436	45.30573656	−4.703276544	−38.90103066	45.00765675	−3.661401777	−39.2220517	44.395	−7.45	−40.77
7	49.4800024	−2.934390976	−38.40625798	50.38564715	−2.778069792	−39.12469293	50.36246	−3.622297424	−38.4330936	49.68	−2.065	−39.325
8	57.64789331	−45.75786819	26.92868623	57.11132373	−46.40453496	27.45183966	57.00311629	−46.22108477	27.28008325	57.33	−46.3	26.675
9	56.64130722	−46.56510507	23.48812562	57.48377773	−46.56260752	23.3550455	57.63389076	−46.89253115	23.89426202	57.845	−46.925	23.425
10	63.65420835	−36.21338151	−9.10966771	62.74801063	−36.0197361	−9.279197521	62.61772191	−35.91766043	−9.323755964	62.4	−40.11	−10.485
11	53.48344732	22.4298452	−32.59205308	54.79653185	18.65495821	−30.38293903	53.78041522	21.48711747	−30.94627913	55.81	19.38	−29.795
12	50.03361949	36.50784881	29.79284017	50.42399191	36.5407766	29.68016091	50.3470072	36.71930433	30.47132135	51.13	35.715	31.095
13	51.30491917	36.24134569	12.59675248	51.45534141	35.80168564	13.43340864	51.21561397	37.07083158	14.15125529	51.78	35.8	13.435
14	55.30790745	40.37459087	−22.57209298	56.02551125	38.74997706	−21.9830629	55.15053405	39.46093151	−22.55396884	56.335	38.375	−22.495
15	59.98259118	14.57412285	−26.17994018	58.93645184	16.6958397	−29.27955889	59.69340644	16.61841689	−28.89935068	59.74	16.81	−28.46
16	64.21884343	−5.288958172	46.38881345	64.31294409	−4.911866567	46.86935701	66.27703833	−6.166102731	47.44548053	65.625	−6.285	49.225
17	65.7070991	−6.442075095	36.20919113	66.85054033	−7.712813626	36.90074131	66.77709405	−7.977421475	36.42236323	66.85	−7.335	37.735
18	69.60491065	−1.037148255	−2.770681388	70.37226642	−1.596375953	−2.455958937	70.67463762	−1.293578523	−2.200244341	70.68	−1.46	−1.67
19	72.65007273	3.537145056	−22.32841862	72.23061792	2.29386843	−22.11535664	71.59910733	3.431581274	−22.54104705	72.645	2.485	−21.26
20	72.08795983	−29.96323758	40.13057215	72.25397659	−30.39104875	40.1337103	71.95075054	−30.10347092	40.20062779	72.835	−31.165	41.475
21	66.48456231	−20.21942868	−30.83197078	66.14133647	−21.10753395	−30.83456744	65.85752001	−19.99946753	−31.98617333	66.97	−20.545	−31.015
22	48.26430435	43.46637054	−20.13826511	48.39841061	43.55834291	−20.8354886	48.06351137	42.76473015	−19.84975557	49.42	43.245	−20.47
23	93.07110056	0.480398054	−2.210781798	93.11777941	0.584249954	−2.469123102	93.11080211	0.040906703	−1.587706161	93.92	0.01	0.695
24	73.81490925	−29.41775476	33.27634725	74.33651838	−29.43069921	32.88192287	74.67380491	−28.8474067	32.01915781	75.155	−29.28	31.625

Table A6. Cont.

Patch	Image 1			Image 2			Image 3			Original		
	L*	a*	b*	L*	a*	b*	L*	a*	b*	L*	a*	b*
25	71.32022776	−33.40404073	25.23824696	71.01446893	−33.60332196	25.21506174	71.30792479	−33.40541908	25.45652715	71.915	−33.615	24.76
26	46.68831314	42.58627162	3.062398771	46.74901432	42.91059873	3.062749905	46.39141549	42.38376149	3.27596508	47.455	42	3.665
27	90.28364574	−6.854389001	32.3831039	90.42456269	−6.829564195	32.51572614	90.42190425	−6.63963252	32.58766509	91.015	−6.76	34.29
28	82.50956456	−18.99990717	10.51350806	80.01422063	−20.28393592	11.37031179	80.89092256	−20.16587466	11.34547522	81.745	−20.435	11.78
29	73.33739054	−30.95225716	19.40688436	71.84133788	−32.36122918	18.41730369	72.0072174	−32.27810017	18.8509576	73.755	−31.535	20.955
30	46.50785307	39.62036404	25.12591481	46.34267773	39.6135048	24.53361539	46.34629848	39.84829913	25.04918565	46.955	39.015	26.085
31	88.45744974	−7.906646108	57.84993681	88.49462709	−8.32230438	58.24990381	88.24843655	−7.622930025	57.92400165	89.235	−7.905	59.555
32	83.88535305	−13.30459614	−5.564840146	84.08026642	−13.40205548	−5.859610651	83.85563609	−13.36227692	−5.953287447	84.925	−13.245	−3.92
33	73.21308917	−28.78059649	11.07225833	73.73154538	−29.39418271	11.04043945	73.18691027	−29.62804501	12.06571999	75.275	−29.28	12.69
34	79.01732041	−20.29382547	−8.176490524	79.41025279	−20.52516119	−8.682696938	78.91898245	−20.62018708	−8.898033216	79.82	−20.945	−7.245
35	87.00249335	−7.020227093	69.82751812	86.75581835	−7.179495586	69.33743374	86.9331797	−7.228633166	69.6590348	88.04	−7.175	68.67
36	54.21921216	51.33665913	29.46916049	54.58484303	51.22193464	28.8370207	54.49649627	50.98302206	29.54797478	55.125	50.84	28.665
37	77.42188163	−22.69954922	−10.0060581	77.6539603	−22.63438376	−9.284716396	77.53926332	−22.56759932	−9.171210902	78.02	−23.11	−8.98
38	82.14247216	−18.94488655	13.26913168	82.47374178	−18.50403528	13.67768467	82.34169714	−19.17354408	14.39332038	82.445	−19.19	13.545
39	74.6795461	23.0498015	−14.40657766	74.05760471	23.99370221	−14.57818443	73.77100334	24.11986026	−14.97090437	75.82	23.17	−12.91
40	58.74814918	48.8943852	13.32299863	57.90531265	49.23749714	13.53960653	57.88969281	49.03545882	13.49674336	58.49	49.665	13.86
41	34.00711073	15.50461585	4.482104618	34.11627233	15.56756911	4.528799614	33.73802154	15.70892813	3.88781182	34.545	15.52	4.59
42	72.51590328	−30.49188942	21.35302706	73.89692325	−30.49603893	20.62636475	74.02141264	−29.88705754	21.58093684	74.58	−30.12	21.085
43	74.45805708	24.75571606	6.41500533	74.95010895	25.22233078	5.529691164	74.63898149	25.6090696	5.575160316	76.095	24.72	6.005
44	66.76113343	30.13676456	42.17669416	66.88059822	29.73851876	41.89147551	67.32930276	29.67776414	42.15720388	68.045	29.53	41.12
45	68.24841598	28.00269266	52.5087662	67.55520813	28.49236469	52.51153519	67.95354718	28.25035814	52.87297196	68.8	27.215	52.515
46	66.44909564	32.69122225	−18.50110907	66.32350203	33.37664642	−19.27730772	66.19496683	32.34189712	−18.77948671	68.265	31.125	−18
47	66.21398864	43.99953714	−7.021793046	66.66619238	43.97419765	−6.757800389	67.65411659	42.85463761	−5.779391763	67.005	43.815	−5.98
48	61.73879841	42.88171883	18.83311482	61.65652079	42.69096862	19.56759196	61.86388135	43.5191143	19.12725871	62.805	42.22	18.4
49	56.67523339	47.13397931	34.18309709	57.26003779	46.73922542	33.84911735	57.61481012	48.11950726	34.58617466	58.235	46.315	32.82
50	62.59281215	37.61749504	−21.18990518	63.11295691	36.71794436	−20.57947787	64.28692969	35.71225626	−19.78381227	65.14	35.48	−19.095
51	62.1415377	51.61772784	−10.88835868	62.17949374	51.23244091	−9.897631548	62.34023511	51.14798066	−9.767120092	63.07	51.21	−9.9
52	35.41609033	19.81918853	−18.97164343	35.4608512	19.58797471	−18.50022004	35.52057965	19.31963695	−18.54447711	36.6	19.215	−18.575
53	71.10158073	−33.93939337	26.74320247	71.21066761	−33.19746135	26.44245439	71.28116265	−33.2988326	26.30160819	72.15	−33.225	28.21
54	67.65400795	−11.69704331	−28.7533471	67.70258186	−11.95497529	−29.28023134	66.75588533	−11.99225353	−29.55023339	67.965	−11.78	−28.46
55	63.43585511	−35.45521782	−10.27796064	64.72563028	−36.85011795	−9.150307138	65.28151471	−37.06127014	−9.385524612	65.98	−36.625	−9.57
56	59.38416043	−44.3840514	26.87639908	60.60024603	−44.0027636	27.14925774	60.15378776	−44.14909011	26.81347731	60.815	−45.05	27.745
57	59.32569875	−41.16143746	32.27217877	59.47200176	−40.99337939	32.44976041	59.55199903	−41.57213205	32.56581901	59.925	−41.845	32.88
58	51.6892684	1.924673318	−37.12716518	51.99219103	1.448863089	−36.66665187	51.7417639	2.19955439	−37.01007333	52.705	2.285	−36.88
59	46.35377563	8.006324837	−38.88823463	46.81628611	7.634440672	−38.7109568	46.47152056	7.63538707	−38.91666441	47.38	7.92	−38.2
60	41.28071328	−1.03201906	−3.55135029	41.26454046	−0.452501366	−4.091557678	41.85800808	−1.679658484	−3.410377066	42.445	−1.245	−2.34
61	41.26734932	−1.976209975	16.12941767	41.35594998	−2.025510365	16.31712316	41.21703307	−2.074874135	15.94274143	41.69	−2.275	16.61
62	46.57937246	6.27645001	−38.95839974	46.06207719	5.998004298	−38.95974847	46.31250652	6.035975669	−38.56982331	46.575	6.655	−38.765
63	38.90798774	18.54048787	−37.17188033	39.50826053	18.12910522	−36.6680683	39.02959357	18.42266151	−37.01079729	39.87	18.085	−36.39

Table A7. Average digital L*, a* and b* coordinate values for each one of the 64 color patches in the calibrated images 4, 5 and 6, compared to average spectrophotometer values taken from the original printed chart.

Patch	Image 4			Image 5			Image 6			Original		
	L*	a*	b*	L*	a*	b*	L*	a*	b*	L*	a*	b*
0	27.84390045	1.532977499	−2.312307639	27.41081792	1.737681612	−2.670935388	27.79152096	1.871001564	−2.531855095	28.48	1.76	−1.79
1	30.77326569	3.216858759	−16.41625956	30.35910056	3.115652151	−16.3796545	30.83719226	4.032367902	−17.55928818	31.275	3.41	−16.695
2	36.92767383	5.398406632	−36.32233275	37.39013718	4.956958697	−35.69608371	36.9929957	4.645112842	−35.38059606	37.21	5.7	−36.18
3	43.04393163	1.616783924	−40.39496303	43.49049481	1.344461059	−40.60794755	43.58262494	1.556095019	−40.3288702	43.535	1.555	−40.78
4	37.62633246	−23.83091304	6.693353345	37.66889697	−24.11327243	7.104325353	37.76057215	−23.43176663	6.320302832	38.09	−25.245	7.95
5	39.37751796	−23.61478952	−6.950803625	39.54331235	−23.7936065	−6.974861526	39.48432712	−23.38383483	−6.895037051	39.515	−23.895	−7.49
6	44.88009847	−4.140929296	−39.00471387	44.09932943	−3.664806806	−39.33595433	44.47252457	−3.617463692	−39.50262456	44.395	−7.45	−40.77
7	49.75008095	−3.788442272	−38.23445099	49.60937163	−3.218457094	−38.76833414	49.80080886	−3.350698281	−38.36027301	49.68	−2.065	−39.325
8	56.41657275	−46.12144505	26.46186433	56.6990077	−46.15092157	27.09728734	56.75370742	−46.35943594	27.08931839	57.33	−46.3	26.675
9	56.54594173	−46.3007017	23.24589574	56.96122101	−46.50371075	23.56054313	57.20099135	−46.8826121	23.13109667	57.845	−46.925	23.425
10	61.95869478	−35.33171643	−9.665631111	61.90884303	−35.69720656	−9.316756386	62.06297994	−35.73662427	−9.452868762	62.4	−40.11	−10.485
11	54.00920222	20.29430904	−30.14095169	54.02455834	20.15519017	−30.19445669	54.04419362	20.57563394	−30.59465885	55.81	19.38	−29.795
12	50.76306998	36.25565214	29.70014864	50.3211656	36.45044816	29.97426354	50.52162565	36.00513667	29.46118274	51.13	35.715	31.095
13	51.37777399	37.14082938	13.20023239	51.04360166	36.68920424	13.35639403	51.32697868	35.7414097	12.4928668	51.78	35.8	13.435
14	55.1504675	40.30350427	−22.56006047	55.68356177	38.30397244	−22.63603484	55.38231577	38.95463951	−22.03471668	56.335	38.375	−22.495
15	59.24732272	16.29567805	−29.06919945	58.71858825	17.33657072	−29.70894535	59.90868104	15.54335443	−27.79561018	59.74	16.81	−28.46
16	64.99936658	−5.366673248	47.41621035	65.26113083	−5.349297529	47.05142287	64.71565361	−5.034006976	46.52147567	65.625	−6.285	49.225
17	66.36652028	−6.773636925	36.47070555	66.75256872	−7.083925787	36.35952388	65.8622864	−6.864688499	33.78120685	66.85	−7.335	37.735
18	69.67225494	−1.218297215	−2.84388521	69.37335967	−0.662208688	−3.406473757	69.8910629	−1.573397502	−2.878272657	70.68	−1.46	−1.67
19	72.34826247	3.340522502	−22.04717223	71.36513371	2.631122412	−22.03887316	71.98056399	2.30122554	−21.11391197	72.645	2.485	−21.26
20	72.2838467	−29.95413074	39.4965475	72.53812741	−30.3258083	40.79854986	71.85883893	−30.11371852	38.61454208	72.835	−31.165	41.475
21	66.58398805	−20.93859228	−30.66555979	66.28450473	−20.9867504	−30.68362005	66.48544136	−21.47761298	−30.471786	66.97	−20.545	−31.015
22	48.64340965	43.40890309	−20.60638635	48.69330774	42.84511931	−20.21727217	48.81560534	43.00231525	−20.15166313	49.42	43.245	−20.47
23	92.97916591	0.446472546	−2.483552367	93.13164243	0.422363543	−2.034398905	93.02492933	0.391578784	−2.250901249	93.92	0.01	0.695
24	74.77668562	−29.00534655	32.37985556	74.57748087	−29.45753379	33.41747332	74.19571566	−30.11442841	32.39875595	75.155	−29.28	31.625
25	70.99344272	−33.318415	24.55518008	70.78850489	−33.65122679	25.55838734	70.99951706	−33.57579581	25.83588231	71.915	−33.615	24.76
26	46.8020554	42.81391285	2.97779734	46.86301629	42.68453848	2.811921646	46.95298994	42.2792263	3.73614871	47.455	42	3.665
27	90.22558813	−6.453797055	31.83386212	90.63254541	−6.592121594	32.14548706	90.29284704	−6.965746589	32.39056074	91.015	−6.76	34.29
28	81.59970575	−20.10374902	11.48453364	80.6446357	−19.6682594	10.72041796	81.31709195	−19.62525943	10.66544381	81.745	−20.435	11.78
29	72.71040797	−31.55012439	19.5560338	72.98182861	−31.51650057	19.55318455	72.95892037	−30.84349914	18.44483102	73.755	−31.535	20.955
30	46.4140835	39.71162219	25.09340969	46.01584427	39.92933523	25.05734799	46.10990736	40.1638031	24.27057337	46.955	39.015	26.085
31	88.19116676	−7.047206653	57.10792246	88.34897451	−7.7053078	58.11172379	88.90342919	−9.55486924	61.86337777	89.235	−7.905	59.555
32	83.78760412	−13.58129619	−5.726754646	83.99850325	−13.62228723	−6.116456573	83.81722249	−14.22508637	−5.894983991	84.925	−13.245	−3.92
33	73.92283188	−29.28117022	11.75938948	73.99294482	−30.04479244	10.83242998	74.00723015	−28.82117684	10.88796764	75.275	−29.28	12.69
34	79.05423237	−19.87488283	−9.224430282	78.26841816	−20.3675405	−8.972055987	78.92438851	−20.5950793	−8.709536818	79.82	−20.945	−7.245
35	87.08674965	−7.379032201	68.93190538	87.15988747	−7.517826925	68.69853808	87.21992733	−7.483877156	70.44692014	88.04	−7.175	68.67
36	54.39926645	51.31999718	28.88670075	54.54261252	51.05624992	29.52646105	54.58847154	51.54817467	28.16391904	55.125	50.84	28.665
37	77.36079365	−22.83814087	−9.822379522	78.46512281	−22.15566897	−8.468952358	77.74286813	−22.69127103	−9.546446072	78.02	−23.11	−8.98
38	82.23812975	−19.04895803	13.26759554	81.64180906	−19.3600212	12.88463604	81.90436273	−19.01697648	12.65952959	82.445	−19.19	13.545
39	74.42287724	23.87039033	−14.48210889	75.49405339	23.6835711	−14.52058157	74.51783729	23.44230011	−14.43597174	75.82	23.17	−12.91
40	57.68746247	49.75047616	13.33369883	58.10647566	49.45586416	13.44460805	58.10289807	48.54696528	13.90035983	58.49	49.665	13.86
41	33.8926024	15.11644438	4.726133253	33.94353089	15.68111274	4.518144197	34.55863326	15.16841252	5.055806652	34.545	15.52	4.59
42	73.72016441	−30.05461112	20.8987134	73.5743727	−30.60018683	20.84194963	73.96029366	−30.19000019	20.96467836	74.58	−30.12	21.085
43	75.57905087	24.33346993	5.824691664	75.60961243	23.87819013	5.636479222	75.59082187	23.99544879	6.355855812	76.095	24.72	6.005
44	67.10110665	29.87567716	42.08197067	68.00017216	28.59153204	41.82494348	67.25353391	29.50611354	41.53198149	68.045	29.53	41.12

Table A7. Cont.

Patch	Image 4			Image 5			Image 6			Original		
	L*	a*	b*	L*	a*	b*	L*	a*	b*	L*	a*	b*
45	67.84234029	28.47800278	52.38774641	67.88555284	28.283168	52.43877572	68.1049305	27.68847906	51.96253961	68.8	27.215	52.515
46	67.29419297	32.45270154	−18.72940253	66.41210453	32.19712394	−18.29168314	67.07999475	32.98536437	−18.93311843	68.265	31.125	−18
47	66.44701938	44.04136086	−6.672555137	65.13438401	44.52075821	−7.031626679	66.40253684	43.69801067	−6.071740707	67.005	43.815	−5.98
48	61.89433872	42.51487662	19.17677075	62.027266	43.27356312	18.57542136	62.04470719	41.92002657	19.793539	62.805	42.22	18.4
49	57.10173987	47.03817212	32.949233	57.56402988	46.57118939	33.5481	57.151204	47.12373982	33.39486081	58.235	46.315	32.82
50	63.34778726	37.19859549	−20.46099663	62.70575672	37.32964234	−20.59693608	63.59747363	36.73912531	−20.16073681	65.14	35.48	−19.095
51	61.80842436	51.49748147	−10.26900052	62.46940458	51.23127861	−9.865212823	61.9047395	51.45669871	−10.37842474	63.07	51.21	−9.9
52	35.6771577	19.56469581	−18.67552308	35.51077334	19.41240179	−18.7925384	35.78880916	19.28150214	−18.81884105	36.6	19.215	−18.575
53	71.16409447	−33.05460362	27.09181741	71.15463322	−33.42379696	26.61794327	71.35643318	−32.82270017	25.42213725	72.15	−33.225	28.21
54	68.03423829	−11.97115757	−29.19951462	65.67275917	−12.15639463	−29.80563454	67.6427247	−12.45192684	−29.09653324	67.965	−11.78	−28.46
55	65.935735	−36.75875331	−9.834695824	65.48147707	−37.43557212	−8.698199313	65.31934028	−36.48557493	−9.973603596	65.98	−36.625	−9.57
56	60.60535657	−44.22971739	26.95168055	60.7284262	−44.04361548	26.43035225	60.07665432	−42.5439807	26.1479209	60.815	−45.05	27.745
57	59.70494059	−42.09425086	32.71218852	59.49296786	−41.52610552	32.12258198	59.66316454	−41.14416482	32.57617081	59.925	−41.845	32.88
58	52.21207176	2.085574612	−37.46221874	52.57975632	1.564442766	−37.05319638	52.09858633	1.731547076	−36.50118471	52.705	2.285	−36.88
59	46.71002179	6.598224464	−38.0014159	47.33400512	7.09793511	−38.38330866	46.71249193	7.436372746	−38.58369272	47.38	7.92	−38.2
60	41.69409211	−0.836800752	−3.727497692	42.15542728	−0.539986863	−4.025229426	41.98625942	−0.566872976	−3.952530791	42.445	−1.245	−2.34
61	41.0614387	−2.499101764	16.17326276	40.80795927	−1.009781665	15.83436714	41.30940593	−2.457603144	15.93440677	41.69	−2.275	16.61
62	46.19283598	6.090939737	−39.34280119	45.71967742	6.483745888	−39.42299546	46.30773015	5.790182427	−38.63653165	46.575	6.655	−38.765
63	39.18429948	18.40006815	−36.42126271	39.15706622	18.15166614	−36.37625527	39.4500688	18.58314654	−36.75236874	39.87	18.085	−36.39

Acid-Free Laminated Paper white patch drifting between hours 0-144, represented in the a^*L^* , b^*L^* and a^*b^* planes

Figure A1. Projections of the a^*L^* , b^*L^* and a^*b^* planes depicting the evolution of the CIELAB coordinates of the white patch in the Acid-Free Laminated Paper along time. Following the arrows, it can be seen that its degradation is not linear nor uniform.

Figure A2. Projections of the a^*L^* , b^*L^* and a^*b^* planes depicting the evolution of the CIELAB coordinates of the white patch in the Acid-Free Paper along time. Following the arrows, it can be seen that its degradation is not linear nor uniform.

Figure A3. Projections of the a^*L^* , b^*L^* and a^*b^* planes depicting the evolution of the CIELAB coordinates of the white patch in the Forex Smart along time. Following the arrows, it can be seen that its degradation is not linear nor uniform.

Figure A4. Projections of the a^*L^* , b^*L^* and a^*b^* planes depicting the evolution of the CIELAB coordinates of the white patch in the Glasspack along time. Following the arrows, it can be seen that its degradation is not linear nor uniform.

Figure A5. Curves in the CIELAB space depicting the evolution of the CIELAB coordinates of the white patch for all four materials along time. Red: Acid-Free Laminated Paper; Blue: Acid-Free Paper; Green: Forex Smart; Black: Glasspack.

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