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Design and validation of tailored colour reference charts for monitoring cultural heritage degradation

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Abstract

Colour changes of cultural heritage objects can be related with degradation of materials, thus a proper colour monitoring system can be used to detect conservation problems. With this purpose, a monitoring methodology for cultural heritage preventive conservation based on tailored colour reference charts and image analysis is proposed.

Reference colour charts have been designed and tested for use in museums. Charts containing 64 colour patches have been printed using high-stability inks on 4 different substrates: Acid-free paper SkyLight, Acid-free paper covered with a propylene film, FOREX® and GlassPack. The stability has been studied by accelerated ageing in an UV chamber, and the harmlessness of the materials by Oddy Test. The final selection of material, laminated paper, is a balance between the colour change upon ageing and the performance in the Oddy Test. Using this material and the proposed design, colour change of copper and silver coupons has been assessed using images that are adjusted and calibrated by an adaptive calibration framework employing a given set of reference colours which homogenises the visual information in the supplied images. Thus, regardless of the camera of origin, any processed picture will deliver reliable information of the state of the colour in the metal surfaces at the moment it was taken.

Results demonstrate the adequacy of the approach and the design for colour calibration, so these charts can be used to monitor colour change of sensitive materials –metal coupons– using photographs. As colour change of reference metals is a consequence of corrosion by environmental factors this may be used as a measure of air quality in museum environments. This methodology can be used to design a low-cost preventive conservation tool, where colour change of metal coupons –or other reference materials– can be followed through image analysis of pictures taken periodically by conservators or visitors, introducing citizen science in the conservation strategy.

Keywords: Colour change, Corrosion, Image analysis, Oddy Test, Preventive conservation, Artificial ageing

Introduction

Degradation of cultural heritage materials is commonly associated with colour change, e.g., tarnishing of silver, yellowing of varnishes or colour fading of certain pigments. Though these alterations cause relevant visual changes, as their progress is slow, it may take some time to draw attention to the problem. An adequate system to detect these changes would improve conservation of heritage collections.

Colour variations have been used in heritage studies for evaluating stone soiling and decay [1–5], degradation of paper [6], varnishes [7], pigments [8], to quantify metal corrosion [9, 10] and for detection of defects on fresco [11]. This relation between colour and decay can be used to design a preventive conservation tool based in

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a systematic monitoring of colour change to detect conservation problems in heritage objects in museums and outdoor monuments.

Colour change can be measured periodically on real objects to assess their condition as in the previous examples, or on reference materials that react when exposed to degradation agents (light, humidity, or volatile organic compounds) to detect possible threats. For instance, blue wool standards, metal coupons or acid-sensitive strips can be used as visual alerts for light-damage, sulphur compounds or acids [12, 13]. These colour changes can be measured using a colorimeter or a spectrophotometer, obtaining accurate data for colour. However, this requires access to this specific piece of equipment, direct contact with the object to be measured and is time consuming. With the popularization of digital cameras, these devices have been proposed as an alternative, low-cost system to measure the colour change [14]. These devices are not intended for colour measurement, so each sensor has different response. Therefore, in order to use digital images for colour measurements, a proper calibration of the image is required, which is usually done by comparison with results obtained from a spectrophotometer or a stable colour reference chart [2, 15, 16]. This methodology has been explored by Brigham et al. [16] to use crowdsourced images from mobile phones for colour measurements. Pictures of an X-Rite ColorChecker®chart were taken with different smartphones, adjusted with an open-source package for image analysis and compared with direct measurements made with a colorimeter.

Standard photographic colour charts as X-Rite have the advantage of being a known standard of validated stability, but they have not been tested for use in proximity of heritage objects -it is known that many materials can outgas harmful volatiles-, the selection of colours has been made with other purposes (similarity to typical colours in photographs, such as green of foliage, blue of the sky or skin tones) and they are quite expensive for a large-scale use of the system.

Here we propose a further development of this approach, which includes the design and validation of a tailored colour chart and the application of computer image analysis for colour evaluation.

The design and validation of our own colour chart has two major advantages over using standard commercial colour references. The first one is reducing the cost, so this methodology can be used as an affordable monitoring system, that can be deployed in many sites. The second one is that allows the selection of colour, number, and disposition of references in the colour chart, optimizing the references for the calibration of the images. It has been demonstrated, in other applications, that a colour chart specifically tailored to the colours to be measured can yield a better performance than a general-purpose one [17, 18].

Based on these ideas we propose a methodology to design a monitoring system for preventive conservation based on colour change. The system is based on a colour chart with an empty area in the middle, where the reference material for study is placed, e.g. metal coupons, to be used as a dosimeter for degradation agents in a museum environment. Colour change of metal coupons can be followed through image analysis of pictures adjusted and calibrated using the surrounding colour chart of chromatic coordinates. Source images can be acquired either by conservation professionals, other museum staff or, more interesting, by visitors, introducing citizen science in the conservation strategy.

As sensitive material to detect aggressive environments, we use metal coupons. Pictures of the reference charts taken periodically will allow monitoring the museum environment through colour change of metal coupons by computer analysis. For this purpose a methodology to calibrate the images has been developed [15], and an automatized system is being developed to automatically process a large quantity of images.

The aim of this paper is to present the design and testing of the colour chart and the validation of the methodology of image analysis for monitoring colour change, assessing the stability of the materials used (both substrate and inks) and their harmfulness to the metals used as colour sensors. This *proof of concept* may be used for other applications too.

Materials and methods

Materials selection

Colour charts have been printed by Once34 Ltd., using LED-UV Xtreme Pro, (by Deutsche Druckfarben) inks (black, yellow, magenta and cyan) on different substrates. These inks have been chosen for their lightfastness, rated 5 (yellow and magenta) and 8 (cyan and black) to blue wool standard according to the manufacturer. Four substrates were chosen for testing between available printing materials, using as starting reference the indications from the British Museum Oddy Test database [19]: Acid-free paper SkyLight (J. Vilaseca S.A.), Acid-free paper covered with a propylene film (PPT50, by ARclad S.A.), FOREX® (PE foam card) and GlassPack (rigid PVC film, by RENOLIT). Selected materials have been tested for UV stability and possible harmful emissions.

UV test

Non printed (white) and the four basic ink colours (black, yellow, magenta and cyan) on the four substrates were exposed to accelerated ageing using fluorescent UVA-340 lamps and measured periodically for colour change.

Experiments have been carried out using a Q-Lab QUV equipment, according to ISO4892-3 standard. UV exposure has been continuous (interrupted for measurements), with no condensation cycles included in the test, since high relative humidity is not expected to be found in museums. Measures were done at short time exposure at the beginning (2, 4, and 6 h) and then spread out over longer periods of time up to 144 h.

To correlate artificial and natural ageing a "museum year equivalent" has been used, estimating the equivalence of exposure to radiation in a museum based in illuminance levels and assuming the reciprocity principle of light exposure [20]. The irradiance level of the experimental setup (0.76 W m^{-2} nm^{-1} at 340 nm, measured at the plane of the samples as per ISO 4892-3 standard) is equivalent to an average direct sunlight. Assuming the illuminance in daylight is about 100 times the maximum recommended in a museum (30.000 lx in daylight vs. 300 lx in museum), and illumination time of 10 h/day in the museum during opening hours, the light dose received by an object in a museum in 1 year (8760 h) will be equivalent to 36.5 h of accelerated ageing.

Colour measurements

Ground truth colour has been measured with a Konica Minolta spectrophotometer CM-700-d with 6 mm diameter mask D65 as illuminant and at 10 degrees to the observer, in colour space L*a*b*. The complete colour chart was measured after printing, to check the precision and reproducibility of colours. Periodic measurements of the base material (white, no ink), black, yellow, magenta and cyan colours (ink colours) were performed.

Oddy test

Possible harmfulness of volatile emissions from the materials of the colour chart towards the sensitive materials (metals) or other heritage materials in the same space has been assessed by means of Oddy Test. It has been carried out following the "3 in 1" procedure described in [21], with the only modification of using glass hooks to hang the coupons instead of inserting them in the silicone stopper. Copper, silver and lead coupons were exposed for 28 days at 60 °C to different materials in glass tubes. 2 g of each substrate, including paper and inks, were introduced in a glass tube; a small glass vial with 0.5 mL distilled water was placed at the bottom and metal coupons were suspended in glass hooks inserted in the tube cap.

Chart design

Colours for colour charts have been selected to cover uniformly the sRGB space, since this colour space is common to almost every camera acquisition system in mobile phones, which follow Rec. ITU-R BT.709 [22]. The uniform distribution is selected because, unlike other checkerboards, the aim of this chart is to help to automate the calibration over the whole colour space, so the colours are not restricted to certain common skin and landscape tones, as others commonly do. Due to physical restrictions (size of the printed colour chart and size of each colour patch in the chart, needed to have a minimum resolution and avoid edge misleading measurement errors) the colour charts have been designed with 64 colour patches. The distribution in the sRGB space of these colours is shown in Fig. 1.

Image analysis

As sensitive materials, copper and silver have been chosen, as in the Oddy test. These metals are representative of metals in cultural heritage and are sensitive to typical pollutants found indoors (organic acids, mainly acetic and formic, and sulphides)[23]. Although lead is very sensitive to organic acids, previous experience has shown that colour changes are not a good measure of the corrosion of this metal [24], since it lightness can evolve in different directions (towards lighter or towards darker colours) depending on the corrosion process taking place. Pure silver and copper coupons (Goodfellow) cut into 1×5 cm pieces and polished up to 600 grit sandpaper were used as references. Clean, fresh coupons were compared with naturally oxidized coupons for measuring colour change. Coupons were exposed during 9 months in a museum environment (National Museum of Science and Technology, MUNCYT, in La Coruña, Spain) to test the methodology in a real situation.

Pictures of dosimeters with fresh and exposed coupons were taken with a Canon EOS 700D camera. Images were taken with a resolution of 5184×3456 pixels, ISO 200, f/4 and 1/40 exposure, using natural light. Images were

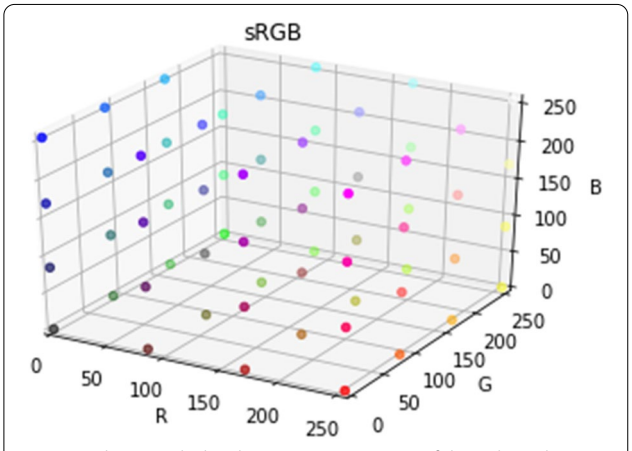

Fig. 1 Colour patch distribution in sRGB space of the colour chart

directly stored by the camera in JPG format. To extract the colorimetric information, pictures taken with the camera were calibrated using an adaptive colour calibration technique developed by authors [15] and compared with those obtained with the spectrophotometer. The calibration process adapts itself to any supplied image, and consists in the calculation of a projection curve. The pixels in the images that correspond to the reference colour chart are projected to their homologue values as measured by the spectrophotometer, and using these as anchor values projection curves that cover the whole RGB space are calculated. Thus, any possible colour value in that space is projected to the corresponding reference space determined by the reference colour chart. The digital colour values corresponding to the metal coupons in the analysed pictures are thus homogenised regardless of their camera of origin.

Results

UV test

Results of colour change over artificial ageing on the base material, represented by the white squares (no ink) can be seen in Fig. 2.

Luminosity (L*) shows minimum variation during UV exposure, except for Glasspack that experiences a linear/progressive darkening from the beginning, being noticeable for the human eye in less than three days. Regarding changes in chromaticity, all materials seem to experience a small change in the first exposition hours.

Materials can be considered stable in the red-green axis, a*, where variation is $\Delta a^* < 0.5$ units for acid free paper, laminated acid free paper and Glasspack, and approximately 1 for Glasspack. Higher variations are observed in the blue-yellow b* axis, with a slight yellowing of all materials and a huge variation for Glasspack. Forex presented the better behaviour in this axis.

As an overall result, acid free, laminated acid free paper and Forex give satisfactory results in this experiment, experiencing minimum colour changes, more accentuated at the beginning and the end of the exposure period, but showing a flat profile for a long time. Glasspack nevertheless, experiences an important and progressive colour variation, tending quickly to yellow under UV exposure.

Considering the colour of inks printed on the different substrates (Fig. 3), it can be observed that the L* parameter is almost invariable, a* experiences minor variations while b* is the most affected parameter, depending on the colour and support. Black can be considered stable in all cases; probably inks protect the base material from light, being this effect more appreciable for black ink. Both magenta and cyan increase their b*value, i.e. turn yellower, while the yellow ink changes in the opposite direction.

Oddy test

As a general result, the Oddy test gave optimum results for Glasspack, acceptable results for acid free paper and failed for Forex (Fig. 4). Silver was not affected by any material, and can be rated as P (suitable for permanent use) according to [21], indicating that no sulphur compounds are emitted from any of the tested materials. These pollutants can be emitted by some papers or the inks, whose composition is complex and unknown, and might include sulphur-containing compounds. Copper got some reddish areas in all cases, attributable to the natural formation of native cuprous oxide layer (cuprite). Forex produced the higher degradation, showing marked iridescence in the lower area, rating this material as U

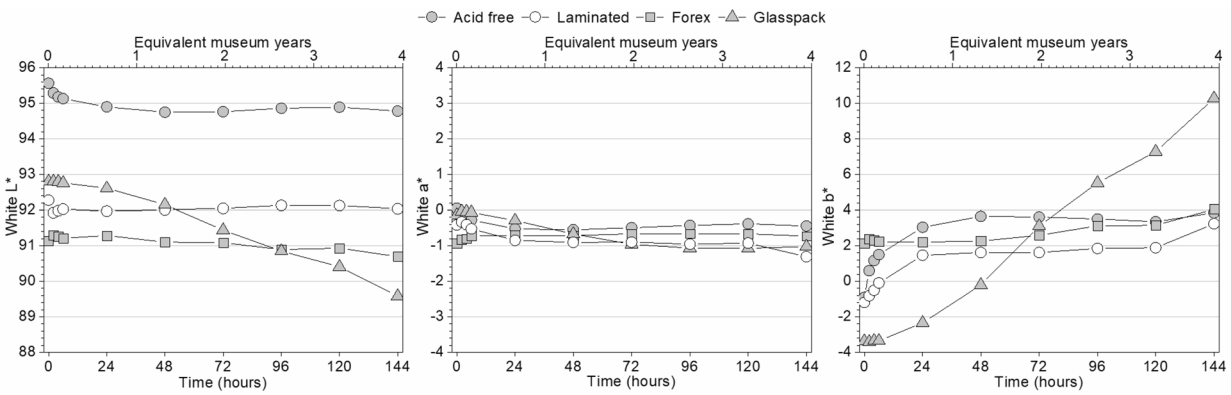

Fig. 2 Variation of L* (black), a* (red) and b* (blue) for the four base materials employed: acid free paper, laminated acid free paper, Forex Smart and Glasspack

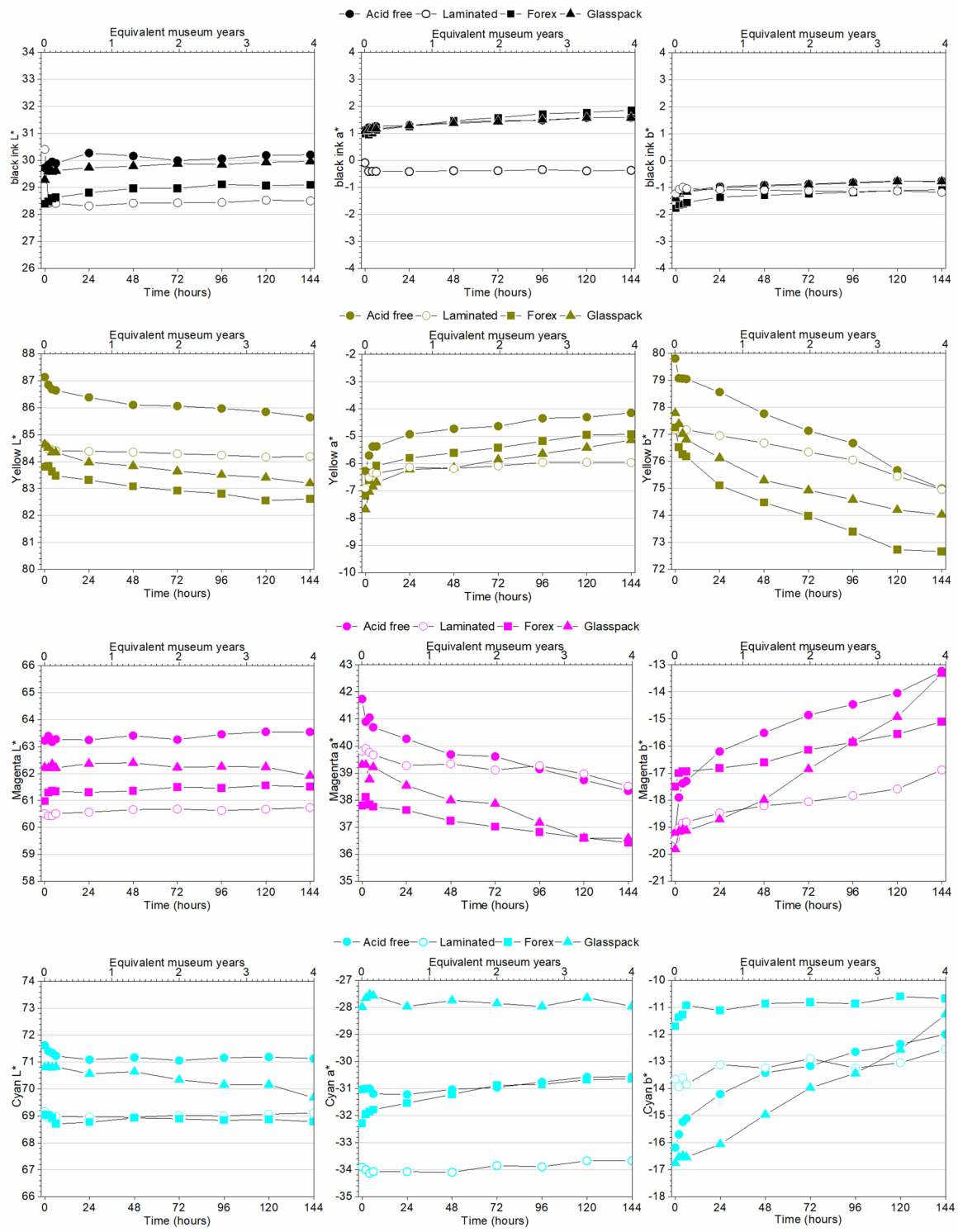

Fig. 3 Variation of L*a*b* chromatic coordinates for black, yellow, magenta and cyan inks over the four base materials employed: acid free paper, laminated acid free paper, Forex Smart and Glasspack

Fig. 4 Results from Oddy test on copper, lead and silver coupons exposed to laminated acid free paper, acid free paper, Forex Smart and Glasspack

(unsuitable for use); followed by acid free paper (rated T, for temporary use). Forex, and with less severity acid free paper, darkened the lead coupon (U), that was unaffected by Glasspack (P). Laminated paper yielded an intermediate behaviour, and slightly tarnished the lead (rated T).

Final design

From these results, laminated acid free paper was chosen as the best option, as combined good UV resistance with low risk of harmful emissions for the exposure period. The colour chart was printed in laminated acid free paper with the design shown in Fig. 5. Then, the two series of metal coupons exposed in the museum for 9 months were mounted on the colour chart and photographed to test the suitability of the whole setup to measure colour change of the metallic coupons.

L*a*b* coordinates were first extracted from the raw images. In a second step, these parameters were obtained from the images calibrated using linear and spatial calibration algorithms developed in [15] and compared with L*a*b* values measured with the spectrophotometer. Comparison of results between direct measurements and calculated L*a*b* coordinates is presented in Tables 1 and 2.

Discussion

In general, the chromatic coordinates obtained from the raw images show large differences with the spectrophotometric values. However, data obtained from the image analysis after calibration show results much closer to those measured with the spectrophotometer, especially in the spatial calibration. Measuring the colour of metal surfaces is challenging, and aspects such as illumination and viewing angles (which are different in the spectrophotometer and the camera), and their interaction with the roughness of the surface can produce differences in the measured colour. In addition to these limitations of the system, differences may also be related with the measured areas. While the colour measured with the spectrophotometer is done in several circular

Fig. 5 Final design of colorimetric references with clean (left) and tarnished (right) copper and silver coupons

Table 1 Comparison of chromatic coordinates measured experimentally and calculated from image analysis for clean and tarnished copper and silver coupons from Fig. 5.

	Clean				Tarnished			
	Measured	Calculated (raw)	Linear calibration	Spatial calibration	Measured	Calculated (raw)	Linear calibration	Spatial calibration
Copper								
L* (10°/D65)	79.66	73.44	74.01	76.71	64.92	70.22	63.36	64.91
a* (10°/D65)	14.30	12.83	19.87	14.09	24.83	25.10	28.00	25.68
b* (10°/D65)	15.10	17.47	13.69	15.34	42.03	48.74	36.50	45.40
Silver								
L* (10°/D65)	91.87	79.60	80.87	81.06	72.44	74.92	66.87	68.45
a* (10°/D65)	0.10	0.20	2.35	−2.11	5.00	4.34	0.65	4.64
b* (10°/D65)	3.63	1.82	−0.63	0.91	26.82	31.19	26.81	26.55

Raw, linear calibrated and spatial calibration calculated values are presented

Table 2 Comparison colour variations between clean and tarnished coupons, measured with the spectrophotometer and calculated from pictures using the two different calibration procedures

Copper	Measured	Calculated (raw)	Linear calibration	Spatial calibration	Silver	Measured	Calculated (raw)	Linear calibration	Spatial calibration
ΔL*	− 14.74	− 3.21	− 10.65	− 11.81	ΔL*	− 18.49	− 4.68	− 14.00	−12.62
Δa*	10.53	12.27	8.13	11.58	Δa*	4.54	4.14	− 1.70	6.76
Δb*	26.93	31.27	22.82	30.05	Δb*	22.42	29.36	27.44	25.64

spots distributed along the surface–which is not completely homogeneous– the colour parameters extracted from the picture cover a wider and continuous area of the coupon. This seems to have a greater impact in the silver coupons, which visually show larger differences between the borders and the central areas of the coupons. The whole area evaluation done by the image treatment is more representative of the real change and will be statistically improved when extracted from a large number of pictures. As mentioned before, this methodology can be used to implement a low-cost preventive conservation tool based in citizen science, using crowdsourced images from museum visitors that can provide a large amount of data. A mobile App is under development to collect mobile phone pictures and test this application.

Our results show that a homemade colour chart, combined with a proper calibration algorithm, can yield results that are appropriate for this application. Using high-end, high-stability commercial colour charts (such as X-Rite) seems therefore unnecessary for this purpose. The work of Brignam et al. [16] has shown that the differences attributable to different camera sensors are higher than the changes of the reference chart measured in our work, indicating that a proper calibration procedure is a more critical step than the high stability of the reference chart. Moreover, if the drift due to fading of the reference is measured using a spectrophotometer, this can be incorporated in the calibration algorithm increasing the precision of the method.

An important question in using home-made charts is how long the colours will stay "stable enough" to serve as reference. As with any accelerated ageing test, a direct correlation with real exposure is not possible, but a rough estimation can be made. Taking into account the approximate equivalence assumed in the experimental section, we can estimate that in the worst case, a similar yellowing of the substrate in a museum having a non UV-filtered illumination will be achieved in approximately 4 years (144 h x 100 = 14,400 h of exposure /10 hours per day = 1440 days = 3.9 years). This is much longer than the typical 1-year exposure that is recommended for indoor corrosion studies [25]. In addition, it has to be considered that high intensity of accelerated aging exposure may produce deviations in the reciprocity principle of light exposure [26] (enhanced by the higher temperatures of climate chambers), thus it is possible to expect an even better behaviour of colour patterns under museum conditions. This will be checked in further studies.

A couple of additional considerations can be made regarding the materials selection for the chart. First, we have used industrial inks intended for outdoors exposure. It should be taken into account that inks used in home and office printers are less stable, so the performance might not be the same. Second, laminated paper, the

material selected for the fabrication of the colour chart, was slightly corrosive to lead. While this should be considered, and it is probably safer to avoid this material in a display case with lead artifacts, it does not pose a problem for the proposed application, as lead has not been included as metallic dosimeter. In any case, in this work we propose a general methodology that can be applied for the development of tailored colour charts using available materials. Finally, the sensitive materials can also be selected according to the needs of the environment or collection to be monitored. The proposed system is flexible enough to include other metals, alloys, pigmented surfaces, or any other material which undergoes colour changes in response to environmental stressors, or is representative of the collection being monitored.

In addition to the economic advantages of creating our own reference charts, additional advantages can be obtained from a tailored design of the reference. As it has already been mentioned in the introduction, reference colours can be chosen to closely match the ones of the sensors used, further improving the precision in the estimation of the real colour from the images [17, 18]. The number and organization of the colour patches can also be modified. For instance, in the design proposed in this work, the placement of sensors surrounded by the reference colour patches, allows to reduce possible differences due to inhomogeneity of the illumination of the sample [14], with is unavoidable when these charts are not used in a laboratory but a real museum environment.

Conclusions

Results obtained in this study have validated a methodology to monitor colour change as an indicator of materials degradation by image analysis. Colour charts have been designed and tested, considering both the colour stability and the absence harmful emissions of corrosive volatile compounds.

Using this chart together with the developed calibration algorithm, we have shown that the accuracy of colour coordinates extracted from pictures can be enhanced, with results more comparable to a spectrophotometer. By incorporating reference sensitive materials on the chart– metal coupons in this case– their colour change upon ageing can be accurately monitored using photographs. As colour change of reference metals is a consequence of corrosion by environmental factors, this may be used as a measure of air quality in museum environments.

This system allows an easy and affordable monitoring of colour change of materials, without contact; and can be applied to develop a low-cost preventive conservation tool for small or medium museums which cannot afford more sophisticated and expensive monitoring systems.

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Authors' contributions
BRB and EC designed the experiments, analysed results and wrote the manuscript. BRB and MTM performed the experiments. JMM, JAR and MAB designed the image processing tool, conceived the colour reference chart, processed the images and extracted metrics for their appropriate analysis. All authors revised and approved the document. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets generated and/or analysed during the current study are available in the Digital.CSIC repository, http://hdl.handle.net/10261/234621.

Declarations

Competing interests
The authors declare that they have no competing interests.

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References

1. Sanmartín P, Vázquez-Nion D, Silva B, Prieto B. Spectrophotometric color measurement for early detection and monitoring of greening on granite buildings. Biofouling. 2012;28:329–38.
2. Thornbush M, Viles H. Integrated digital photography and image processing for the quantification of colouration on soiled limestone surfaces in Oxford, England. J Cult Herit. 2004;5:285–90.
3. Grossi D, del Lama EA, Garcia-Talegon J, Iñigo AC, Vicente-Tavera S. Evaluation of colorimetric changes in the itaquera granite of the Ramos de Azevedo Monument, São Paulo, Brazil. Int J Conserv Sci. 2015;6:313–22.
4. Grossi CM, Brimblecombe P, Esbert RM, Alonso FJ. Color changes in architectural limestones from pollution and cleaning. Color Res Appl. 2007;32:320–31.
5. Gherardi F, Gulotta D, Goidanich S, Colombo A, Toniolo L. On-site monitoring of the performance of innovative treatments for marble conservation in architectural heritage. Herit Sci.; 2017;5.
6. Malešič J, Kadivec M, Kunaver M, Skalar T, Cigić IK. Nano calcium carbonate versus nano calcium hydroxide in alcohols as a deacidification medium for lignocellulosic paper. Herit Sci. 2019;7:50.

7. Martínez Domingo M, Valero E, Huertas R, Durbán M, Espejo T, Blanc R. Spectral information to get beyond color in the analysis of water-soluble varnish degradation. Herit Sci. 2019;7:79.
8. Berrie BH, Strumfels Y. Change is permanent: thoughts on the fading of cochineal-based watercolor pigments. Herit Sci. 2017;5:30.
9. Ankersmit H. Tarnishing of silver: evaluation by colour measurements. Met 2001 Proc Int Conf Met Conserv. Santiago, Chile 2–6 April 2001. 2004.
10. Tétreault J, Cano E, Van Bommel M, Scott D, Dennis M, Barthés-Labrousse M-GM-G, et al. Corrosion of copper and lead by formaldehyde, formic and acetic acid vapours. Stud Conserv. 2003;48:237–50.
11. Guarneri M, Danielis A, Francucci M, De Collibus MF, Fornetti G, Mencattini A. 3D remote colorimetry and watershed segmentation techniques for fresco and artwork decay monitoring and preservation. J Archaeol Sci. 2014;46:182–90.
12. Ankersmit HA, Doménech-Carbó A, Tennent NH. Tarnishing of silver: evaluation by colour measurements. Met 2001 Proc Int Conf Met Conserv. Santiago, Chile 2–6 April 2001. 2004. p. 157–66.
13. Carmona N, Herrero E, Llopis J, Villegas MA. Chemical sol–gel-based sensors for evaluation of environmental humidity. Sensors Actuators B Chem. 2007;126:455–60.
14. Sanmartín P, Chorro E, Vázquez-Nion D, Miguel Martínez-Verdú F, Prieto B. Conversion of a digital camera into a non-contact colorimeter for use in stone cultural heritage: The application case to Spanish granites. Measurement. 2014;56:194–202.
15. Barbero-Alvarez MA, Menendez JM, Rodrigo JA. An Adaptive Colour Calibration for Crowdsourced Images in Heritage Preservation Science. IEEE Access. 2020;8:185093–111.
16. Brigham R, Grau-Bové J, Rudnicka A, Cassar M, Strlic M. Crowdsourcing as an Analytical Method: Metrology of Smartphone Measurements in Heritage Science. Angew Chemie Int Ed. 2018;57:7423–7.
17. Zhang B, Nie W, Zhao S. A novel Color Rendition Chart for digital tongue image calibration. Color Res Appl. 2018;43:749–59.
18. Choi H, Choi K, Suk HJ. Performance of the 14 skin-colored patches in accurately estimating human skin color. IS T Int Symp Electron Imaging Sci Technol.; 2017. p. 62–5.
19. British Museum. Database of Materials Test Results. https://webarchive.nationalarchives.gov.uk/20190801112014/https://www.britishmuseum.org/research/publications/research_publications_series/2004/selection_of_materials.aspx. Accessed 19 Sept 2019.
20. Down JL, MacDonald MA, Tétreault J, Williams RS. Adhesive testing at the Canadian Conservation Institute-an evaluation of selected poly(vinyl acetate) and acrylic adhesives. Stud Conserv. 1996;41:19–44.
21. Thickett D, Lee LR. Selection of materials for the storage or display of museum objects. The British Museum Occasional Paper Number 111; 2004.
22. Recommendation BT.709-6: Parameter values for the HDTV standards for production and international programme exchange. (06/2015). https://www.itu.int/rec/R-REC-BT.709-6-201506-I/en [Accessed 21 December 2020].
23. Tétreault J. Airborne pollutants in museums, galleries and archives: risk assessment, control strategies and preservation management. Canadian Conservation Institute; 2003.
24. Lafuente Fernández DT. La contaminación por COV en museos y exposiciones: Análisis y efectos sobre el patrimonio cultural metálico. Límites y conservación preventiva. Universidad Autónoma de Madrid; 2017. https://repositorio.uam.es/handle/10486/681000 [Accesed 20 December 2020].
25. ISO - ISO 11844-1:2006 - Corrosion of metals and alloys — Classification of low corrosivity of indoor atmospheres — Part 1: Determination and estimation of indoor corrosivity. https://www.iso.org/standard/36651.html [Accessed 14 Jan 2021].
26. Del Hoyo-Meléndez JM, Mecklenburg MF. An investigation of the reciprocity principle of light exposures using microfading spectrometry. Spectrosc Lett. 2011;44:52–62.

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