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Changes in the Visual Appearance of Polychrome Wood Caused by (Accelerated) Aging

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Abstract

This work takes a step towards understanding fundamental aspects of appearance change in cultural heritage. Particularly, we concentrate on the case study of the Hedal Madonna – a polychrome wood sculpture dated to the mid-1200s, and an important object of ecclesiastical art and Norwegian heritage. It is covered with a layered coating that gives rise to complex reflective properties and gives the sculpture a unique appearance. We studied the goniometric, spectral, and chromatic properties of mock-ups manufactured according to medieval techniques, and also carried out accelerated aging. We compared the properties of aged and original mock-ups, and found non-trivial changes in polychrome appearance. While the color of the mock-ups did not change significantly, we observed a noticeable change in their glossiness, presumably caused by structural degradation of the surface. We also found a difference in the goniometric properties of the polychrome material's reflectance as a function of angle. Reflectance distributions that were originally symmetric with respect to angle became asymmetric. These findings will help to understand the original appearance of the Hedal Madonna, as well as aiding the design of appropriate conservation conditions for both the original statue and its recent reconstruction.

Figure 1. *1250s original Hedal Madonna statue (left) and 1990s reconstruction (right). Photo: Eirik I. Johnsen ©KHM, UiO.*

Introduction

Visual appearance and associated properties are critical in the consideration of cultural heritage. Not only do they determine how objects are perceived by observers, but they can also provide valuable information about an object's origins, history, storage conditions, and original appearance. Measurements of these properties may also be used to predict future changes, and help design appropriate conservation conditions by identifying potential threats. Such applications require us to study not only an object's current appearance, but how that appearance changes with age.

Polychrome refers to the decorative practice, widely popular across medieval Europe, of augmenting wooden sculptures and panels with a rich variety of materials, including brightly colored pigments, resins, metals, and their various combinations. Within this broad palette of materials, one particular composite of silver leaf set beneath a yellow pine resin achieves a striking gold-like appearance; whether this was used as a substitute for gold leaf, or for its own special appearance qualities, remains an intriguing question [8][11].

In this work, we concentrate on the case study of the Hedal Madonna, a polychrome sculpture dated to the mid-1200s, and one of the most important pieces of medieval ecclesiastical art in Norway. It was originally located in central Norway at Hedalen Stave Church, which itself dates to around 1163. In the 1980s conservators at the Cultural History Museum of Oslo discovered a threat to the statue's condition, due to the periodical fluctuations of temperature and humidity inside the church (which was electrically-heated in winter), and moved the statue to the museum for restoration. The researchers also created an accurate copy of the statue, according to authentic medieval techniques described in an early fourteenth-century Icelandic manuscript. The reconstruction is now exhibited in the museum, and is itself a valuable object of cultural heritage (Fig. 1). Both the original and reconstructed statues are vulnerable to aging and deterioration, so it is important for conservators to be able to characterize the physical properties of 'fresh' polychrome, predict how they may change with aging, and know how to minimize this.

The initial steps of this study were performed using polychrome wood mock-ups, created with the same medieval techniques by conservator Dr. Kaja Kollandsrud. Square pieces of wood were covered with a chalk ground before a layer of silver leaf is applied, and finally a coating of yellow pine tar resin (details in [8]). Apart from measuring their initial spectral and chromatic properties, we also carried out accelerated aging of the samples in a vacuum oven, with periodical cooling in a freezer, to simulate the temperature fluctuations of natural aging. We studied the changes caused by aging, and found a significant decrease in the glossiness of of samples, likely caused by degradation of the resin's surface structure. We also identified changes in goniometric spectral reflectance of the material.

The rest of the paper is organized in the following way: section 2 describes related works in appearance study and accelerated aging, section 3 discusses the design of the aging protocol, section 4 presents the measurements of unaltered polychrome mock-ups, and section 5 discusses changes in aged samples.

Related works

Material Appearance

While dominant, color does not exclusively determine the visual appearance of materials; instead, objects and surfaces may also be characterized in terms of their glossiness, translucency, transparency, roughness, bumpiness, *etc*. A number of works have been directed towards studying low-level visual features that might support the rapid, robust judgements of materials that observers make [1][9] [6][12].

Other works have investigated the neural processes involved in material perception. In particular, the cortical regions responsible for the perception of glossiness were studied independently by Kentridge *et al.* [7] and Wada *et al.* [14]. A comprehensive review of advances in glossiness perception can be found in [3]. Toscani *et al.* [13] have shown a causal link between gaze behavior and lightness judgments.

However, to the best of our knowledge, studies that relate appearance properties and cultural heritage are rare. A good example is Leonards *et al.* [10] that demonstrates how materials of different appearance might be used in cultural heritage objects to direct observers' looking behaviour.

Accelerated aging

Accelerated aging is a common tool in material studies. It allows experimenters to approximate the natural degradation of a material over time, and to study the associated processes. It also may be used in perceptual science, in order to examine changes in an object's appearance over long time periods, or to demonstrate its stability. To the best of our knowledge, there are no works that study the aging of the 'imitation-gold' material used in the Hedal Madonna, however, some works are dedicated to other types of polychrome.

The natural aging imperfections on polychrome wood were studied by Babita and Timar [2] by the case of an artisanal hanger, originating from Szecklerland, Romania. Wong *et al.* [15] studied polychrome paintings on imperial Qing architecture in China. The authors also studied accelerated aging processes in reconstructed samples. The pipeline of aging they followed included cycles of wet-freeze-thaw (spraying, freezing, and keeping at room temperature) to simulate the relevant weather conditions in northeast China. While relevant to our object, the Hedal Madonna was kept indoors and thus not exposed to rain, and the authors did not seek to evaluate the visual properties of the material, which is our chief concern.

Colombini *et al.* [4] studied imperfections in polychrome paintings caused by the aging of paint binders under UV light. Results showed that UV light aging does not significantly affect the amino acid profile of protein binders, however, visual appearance and spectral properties were not discussed. Another relevant work is the study of resins on eighteenth-century furniture by Derrick [5]. Five natural resins (shellac, sandarac, mastic, copal, and rosin) were cast onto clean thin sheets of aluminum, which is similar to the layer of silver leaf in our study object. The samples were irradiated with a xenon lamp simulating outdoor sunlight. However, our object naturally was not exposed to direct sunlight and UV-radiation.

These and other works helped us to design an aging setup corresponding to indoor conditions in rural northern regions of the Northern Hemisphere, which are directly related to the object history of the Hedal Madonna.

Accelerated aging procedure

Accelerated aging may be used to predict changes of materials over time, or to ”revert” such changes and predict the original appearance of objects with relevance to cultural heritage and archaeology. Our interest combines both of these directions, as we want to both preserve the current state of the statue (and its reconstruction), and also better understand its history.

The protocol for the aging of polychrome samples was chosen to be an accurate approximation to the natural conditions the original statue was exposed to. From conservators, we know that the statue was kept inside the Hedalen Church building in central Norway. In its recent history, electrical heating of the church made the air within the church dry, especially in winter. Considering that during wintertime central Norway may typically reach -20 – -30°C, it is very likely that the statue encountered large fluctuations of temperature and humidity, on both seasonal and daily timescales. Other common parameters of accelerated aging include exposure to ultraviolet light and water spraying. In the case of the Madonna, the statue was not exposed to direct sunlight, neither was it drenched in rain. Thus, we did not apply UV lamp exposure or spraying in the accelerated aging process.

Samples were exposed to the cycled fluctuations of temperature and relative humidity at their extreme values, for an artificial acceleration of aging processes. This procedure was implemented by moving the samples between three environments: a vacuum oven at 60°C and 60 mbar pressure (a warm dry environment), a freezer at -10°C (a cold humid environment), and normal room conditions at 20°C to avoid abrupt changes. Samples spent the majority of the time (up to 500 hours) in the oven under vacuum, and were periodically placed in the freezer for two hours at a time, to cool them to sub-zero temperatures. We considered two hours to be sufficient time in the freezer, firstly because long-term freezing does not accelerate the aging process, and secondly because

Figure 2. *Condensation on the surface of four mock-ups after freezing.*

the air in the freezer stays humid only a few hours after opening it (up to 100% RH). Before and after freezing, samples were kept at room temperature for 30 minutes to make the transition less abrupt. It is worth noting that at room temperature frozen samples collected condensation on their surface (see Figure 2), which could also have been the case in the Hedal Church when heating was started on winter mornings. The 30 minutes period was sufficient for all water droplets to evaporate before returning samples to the oven.

We aged four samples gradually, extracting one of them at each stage, to obtain step-wise information. Only one sample completed the full aging process. As a result, the timeline for each sample was as follows (illustrated in Fig. 3):

- Sample 1: original, unaltered.
- Sample 2: 25h heating → 2h freezing → 25h heating → 2h freezing.
- Sample 3: the same as for Sample 2 → 100h heating → 2h freezing.
- Sample 4: the same as for Sample 3 → 150h heating → 2h freezing.
- Sample 5: the same as for Sample 4 → 200h heating → 2h freezing.

In total, Sample 2 went through 50+4 h of aging, Sample 3 – 150+6 h, Sample 4 – 300+8 h, and Sample 5 – 500+10 h.

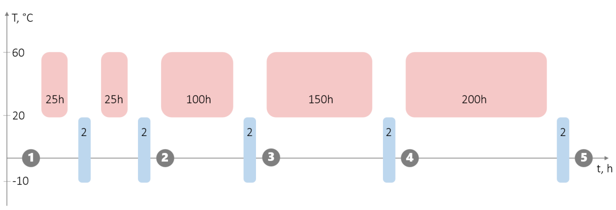

Figure 3. *Accelerated aging timeline. Pink and blue areas represent time in the oven and freezer respectively. Numbered grey circles indicate the endpoints for samples 1-5.*

Analysis of unaltered samples

Before studying the changes caused by aging, we first characterized the unaltered mock-ups. The polychrome material of study has complex visual properties due to the composite structure and translucent top layer of resin. The silver layer beneath also contributes to the apparent glossiness of the surface, and together with the resin on top gives rise to significant changes in appearance dependent on viewing angle (Fig. 5). This motivated us to carry out goniometric measurements, in addition to standard spectral measurements at constant geometry of illumination and reflectance.

The setup we used is illustrated in Fig. 4. The distribution of polychrome layers is considered uniform over the area, and

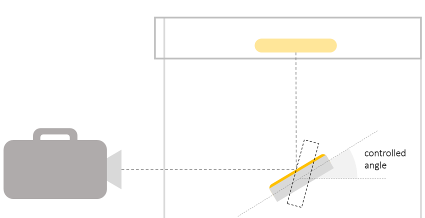

Figure 4. *Experimental setup.*

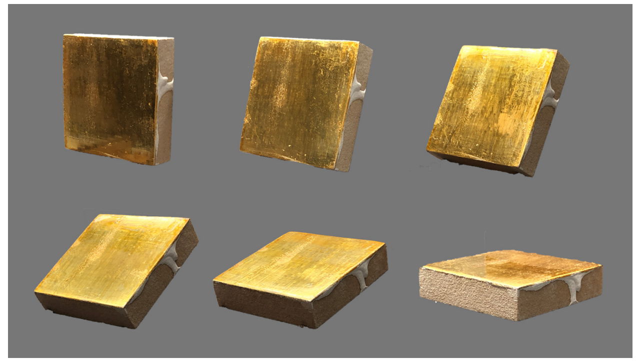

Figure 5. *Demonstration of polychrome mock-up and its color change with rotation under fixed D65 illumination. The background is mild gray (L* = 50).*

assumed to be constant over all five mock-ups (spectral measurements confirm this). Thus, it was sufficient to use conventional spectroradiometry without spatial information. All measurements were averaged over five random positions of samples, to minimize variation due to inhomogeneities in the material. The measurements were performed using a Konica Minolta CS-1000 Spectroradiometer in a commercial light booth under illumination corresponding to the CIE D65 standard. Rotation of the sample was controlled using a custom-made stand, allowing its angle to be measured relative to the horizontal. The angle between the light source and spectroradiometer was kept constant at ≈90 degrees.

Figure 6 illustrates the measured spectral reflectance of the polychrome mock-ups. Each spectrum is plotted with a line color corresponding to CIE L*a*b* coordinates of the reflectance spectrum of the surface under the D65 standard illuminant. The numbers on the right-hand side correspond to the angles in degrees under which the spectrum was measured. Notably, the spectra do not change linearly with respect to angle. Rather, it increases in spectral power, decreases to a local minimum, and further increases. This sequence is poorly perceived on such a plot, and therefore presented in 3D later in the text. In general, we can see the similar distributions of all measured spectral reflectances reaching a minimum in the short-wavelength spectral range, and

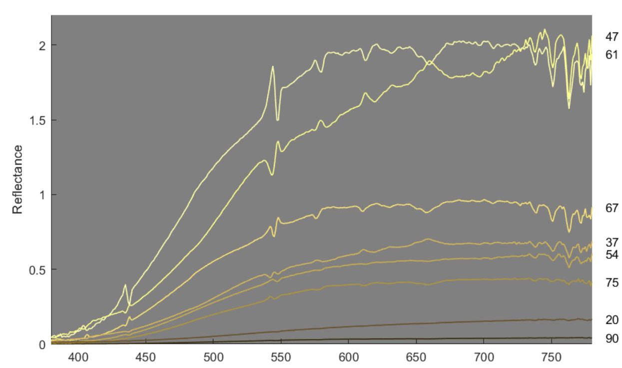

Figure 6. *Spectral reflectance measurements of polychrome mock-ups. The angle of measurement is annotated on the right of the spectrum. Each spectrum is plotted in the color it produces when transformed to CIE L*a*b* coordinates. The background is mid gray (L* = 50).*

ues transformed to sRGB. All color points lie in L*b* plane and hold around 0 on the a* axis, distributing along a straight line, although this distribution is highly non-linear with respect to angle (it may be seen for example that the angle of 54° has a darker color than 47° and 61°). Overall, the range of colors produced is wide, from a dark almost achromatic color with L* = 18, a* = 1, b* = 20, to a very light yellow with L* = 120, a* = -5.8, b* = 69 (all color values are additionally reported in Table 1), demonstrating the complex reflectance properties of this polychrome material.

The goniometric properties of polychrome reflectance can be visualized in 3D coordinates where the x axis corresponds to wavelength, the y axis to angle, and the z axis to reflectance value (Fig. 8). We interpolated the spectra of samples measured at eight different tilt positions, for visualization as a three-dimensional surface. This provides a good illustration of reflectance as a function of an angle. Interpolation was performed according to the Modified Akima cubic Hermite method for angles in the range of 20°–90°, to a step size of 1°. The results are presented in Fig. 8.

Figure 8 illustrates an unusual property of the polychrome material's reflectance function. Most surfaces, including glossy ones, have a single-peaked reflectance distribution, with reflectance reaching a maximum when the angle of reflection equals the angle of incidence (specular reflection) and decreasing to lower levels on either side of the peak, due to scattered light (diffuse reflection). However, in the case of this resin-coated silver polychrome material, we see radically different optical properties. Its reflection profile has two symmetrical peaks, at around 47° and 61°, with a local minimum between them at around 54°. We hypothesise that this effect may be due to double reflection of light: first off the boundary of air and resin, and then, after penetrating, off the silver underneath resin. This observation may be key to understanding the unique visual properties of this polychrome material and requires detailed study.

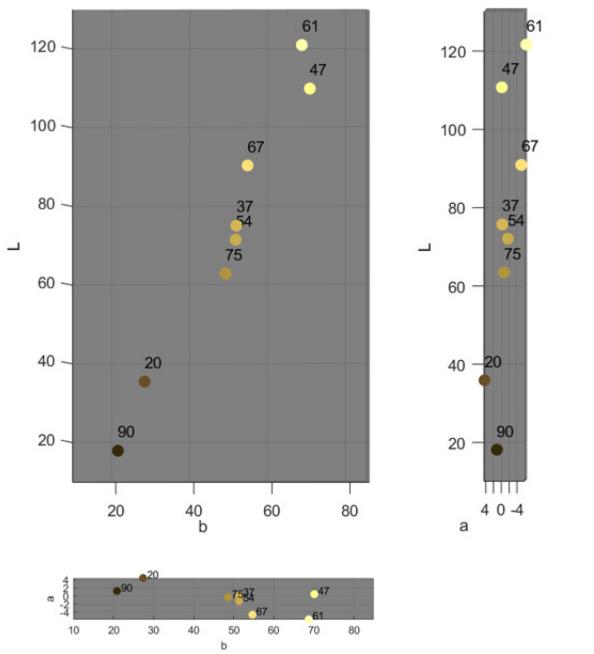

*Figure 7. The colors produced by polychrome mock-ups under different angles plotted in CIE L*a*b* color space. The angles of measurement are annotated near the markers. The background is mid gray (L* = 50).*

increasing to a broad peak in the long-wavelength range. The narrow peaks around 550 nm are caused by fluorescent light source artifacts, while the spectral range beyond 750 nm is noisy due to the low power of the light source in this range.

The locations of the samples colors in CIE L*a*b* space is shown in Figure 7. The coordinates are illustrated in different color planes for better understanding, with the angles of measurement annotated. Colors of the markers correspond to L*a*b* val-

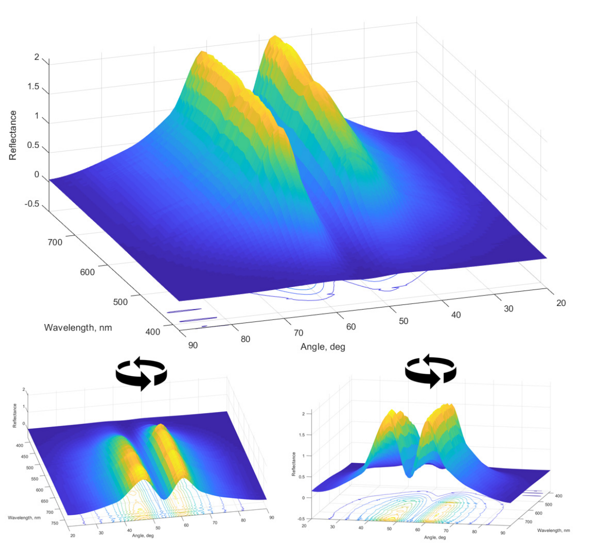

Figure 8. Changes in polychrome spectral reflectance with angle. Two symmetric peaks (around 47° and 61°) and local minimum between them may be seen. Interpolated to a 1 nm × 1° grid.

	Sample 1 L = 79.11 a = -1.88 b = 52.10	Sample 2 L = 81.57 a = -2.14 b = 53.18	Sample 3 L = 81.63 a = -1.65 b = 52.57	Sample 4 L = 79.82 a = -0.60 b = 55.16	Sample 5 L = 81.28 a = -0.27 b = 57.62
Sample 1 L = 79.11 a = -1.88 b = 52.10	0.000	1.729	1.747	1.357	2.456
Sample 2 L = 81.57 a = -2.14 b = 53.18	1.729	0.000	0.363	1.695	1.816
Sample 3 L = 81.63 a = -1.65 b = 52.57	1.747	0.363	0.000	1.627	1.755
Sample 4 L = 79.82 a = -0.60 b = 55.16	1.357	1.695	1.627	0.000	1.242
Sample 5 L = 81.28 a = -0.27 b = 57.62	2.456	1.816	1.755	1.242	0.000

Figure 9. CIEDE2000 color difference between original and aged samples. Measured under D65 illuminant at 54° tilt.

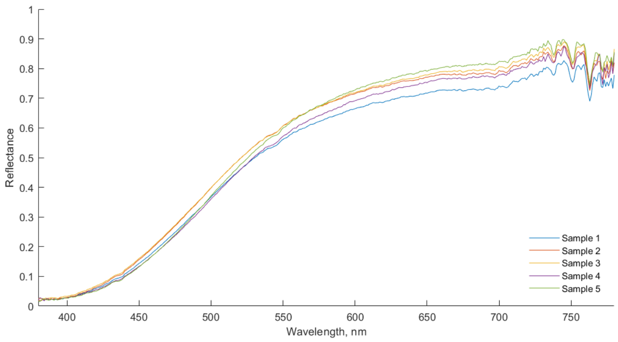

Figure 10. *Spectral reflectance of aged (Sample 2–5) and original (Sample 1) mock-ups. Measured with 54° sample tilt.*

Impact of aging on appearance

After the initial study, four out of five samples underwent accelerated aging, being exposed to extremes of heat and cold, as well as humidity, for the span of up to 500 hours (Fig. 3). This procedure inevitably affected the exposed resin layer of the material, and this contributed to the final appearance of the mock-ups. Further, we present physical measurements analogous to those performed for the unaltered samples, and analyze the differences between them.

When observed at a fixed viewing angle, all the samples are broadly similar in appearance. The chromatic differences between them are less than a *just-noticeable difference*, as illustrated in Figure 9. The top row and left column show the color of each sample under D65 illumination, as rendered from the measured spectral reflectance. The intersection of two samples contains the value of CIEDE2000 color difference between them. This difference is mostly within 2 units of ΔE_{2000}, with only the "oldest" sample giving a difference of $\Delta E_{2000} = 2.46$ compared to the fresh. Figure 10 presents the corresponding spectral reflectance of each sample (54° geometry) and illustrates how similar they are.

Sample 5 was the 'oldest', undergoing the aging process for 500 hours. The general shape of its reflectance spectra (Fig. 11) and location of colors in CIE L*a*b* color space (Fig. 12) are similar to the unaltered material. However, we observe that maximum values of reflectance are almost twice as high, with color values covering a larger range of color space, and almost reaching white at its lightest point. The linear arrangement of all the produced colors in L*b* plane is preserved similarly to the unaltered material. All the measured color values are presented in the following table (Table 1).

The effects of aging are clear when the samples reflectance functions are considered in terms of both their wavelength- and angle-dependence. Figure 13 shows corresponding three-dimensional surfaces after interpolation and allows to compare the reflectance of the original and aged polychrome material with respect to angle. It is clear that the previously symmetric goniometric dependence becomes asymmetric after aging, with the peak at 47° increasing and the peak at 61° broadening out.

Visually, the only perceptual differences between aged and fresh samples are not in color but in glossiness, with the unaltered sample looking considerably more glossy than the aged one. This is illustrated in a photograph (Fig. 14). In keeping with this observation, the fresh sample has a smoother and more mirror-like

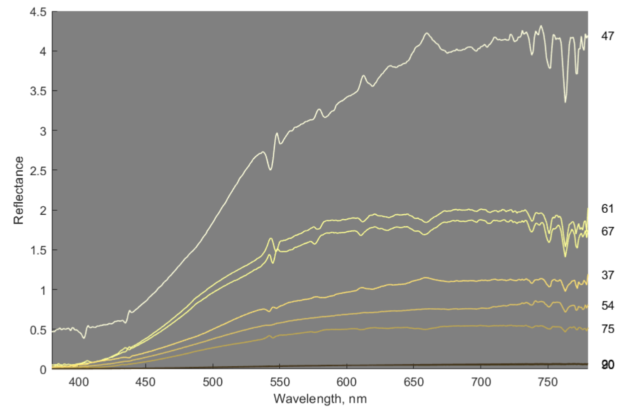

Figure 11. *Spectral reflectance of the aged polychrome mock-ups (Sample 5). The angle of measurement is annotated on the right of the spectrum. Each spectrum is plotted in its corresponding color after conversion to CIE L*a*b* coordinates. The background is mid gray (L* = 50).*

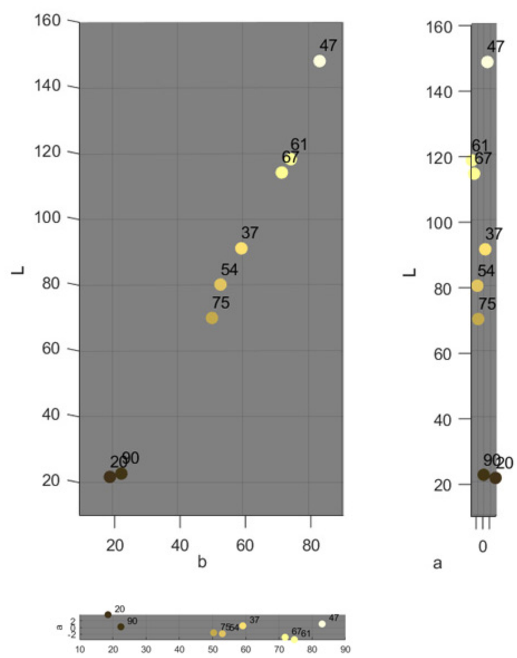

Figure 12. *The colors produced by aged polychrome mock-ups under different angles in CIE L*a*b* coordinates. The angles of measurement are annotated next to the markers. The background is mid gray (L* = 50).*

surface, whereas the aged sample's surface is bumpy and uneven.

We also noticed the difference between samples in macro photos of their surface (Fig. 15). It may be seen that in comparison to the surface of unaltered samples, aged polychrome is visibly damaged and degraded. We did not observe craquelure on the surface but some micro-fractures did appear on a very fine scale. Presumably, freezing of the samples and transitions over zero Celsius contributed to such degradation.

Apart from micro-damage and overall degradation, we hypothesize that the decrease of glossiness could also be caused by thinning of the resin layer. Resin is a naturally amorphous solid,

Measured CIE L*a*b* values of fresh (Sample 1) and aged (Sample 5) polychrome mock-ups.

Tilt	Original			Aged (500+ hours)		
	L*	a*	b*	L*	a*	b*
90°	18.04	1.23	20.88	22.78	0.21	22.42
75°	62.97	-0.32	48.60	70.04	-1.58	50.33
67°	90.36	-4.65	54.69	114.23	-2.95	71.82
61°	120.92	-5.81	68.71	118.25	-3.67	74.62
54°	71.54	-1.26	51.30	80.20	-1.86	52.96
47°	110.00	0.45	70.11	148.18	1.07	82.97
37°	75.18	0.15	51.31	91.25	0.51	59.11
20°	35.69	4.45	27.38	21.87	3.86	18.55

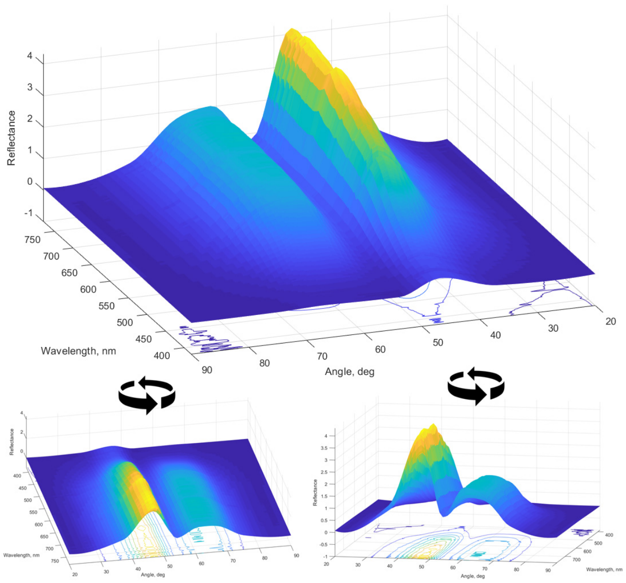

Figure 13. Changes in the reflectance properties of aged polychrome mock-ups with respect to angle. The significant increase in the peak at 47° and the asymmetry of the two peaks can be seen. Interpolated to a 1 nm × 1° grid.

which does not have a crystal structure or melting point. Thus, heating in the oven results in a decrease in viscosity, which may cause a redistribution of resin and its flow to the sample edges or lower areas (the mock-ups were heated in horizontal position). The thickness of the resin layer may also decrease due to some degree of evaporation. This process may explain changes in reflection spectra due to larger amounts of light transmitting through the resin layer thereby causing an increase in the light reflected from silver while the reflection from resin is almost unchanged.

The accelerated aging we carried out may also have produced other effects not covered in this work. Identifying those, as well as understanding which particular processes are responsible for the described changes in reflectance properties and surface glossiness, will require an extended analysis and additional equipment.

Conclusions

This work presents the results of a study into the visual appearance and optical properties of a unique material used in medieval polychrome sculpture. Using mock-ups created with the same artisanal decorative process as used to create the Hedal Madonna in the mid-1200s, we characterized their optical properties.

Goniometric evaluation of the samples' spectral reflectance spectra allowed us to obtain a rich characterization of their chromatic and reflective properties, which significantly determine the material's appearance. We found that the material has a wide distribution of apparent colors for a range of reflectance angles, from dark brown to light yellow, with colors distributing linearly in the L*b* color plane. The material demonstrates surprising goniometric properties, with its reflectance possessing a symmetric duo of peaks.

We also carried out accelerated aging of the polychrome samples, in conditions that simulated the environment to which the Hedal Madonna sculpture has been exposed. Accelerated aging for 500+ hours produced a noticeable difference in the sample's glossiness, with the surface of aged mock-ups becoming less glossy, despite an increase in one of the two reflectance peaks. Close examination showed that the resin surface of the polychrome material underwent structural changes, losing its initial smoothness and evenness.

The changes in mock-ups caused by aging are complex and require additional analysis. It may be beneficial to extend the aging protocol to 1000–2000 hours, in order to reinforce the changes and uncover other potential effects. In addition, the remarkable yet subtle changes in the material's appearance may require comprehensive, psychophysical studies into the visual perception of the material properties of such samples.

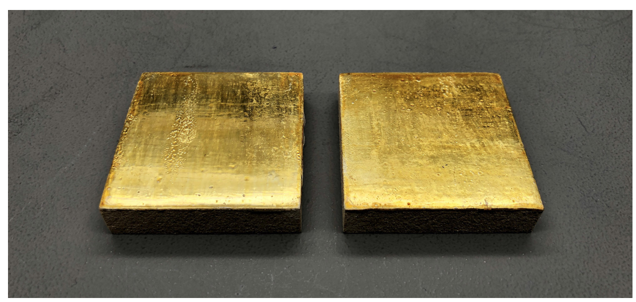

Figure 14. Visual comparison of the glossiness of original (left) and aged (right) polychrome mock-ups.

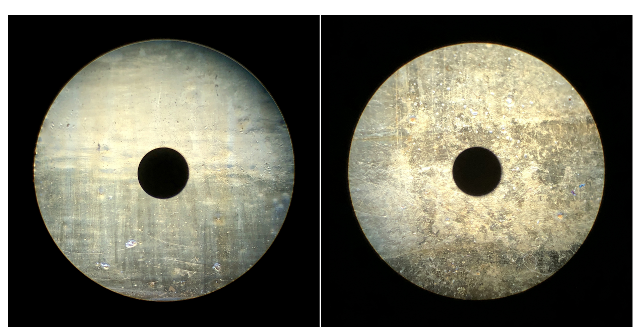

Figure 15. Macro photos of original (left) and aged (right) polychrome mock-ups.

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