ABSTRACT—In this article we summarize research conducted over the past 15 years aimed at understanding the original colors used in stained furniture. It is a synthesis of research, part of which is published, but this article also contains data from internal research reports. We present the results of chemical analysis and the outcome of reconstructions made based on historical recipes and degradation research. We used these findings to retouch furniture with colored light, using beamers controlled by computers, mapping software, and photogrammetry.

1. INTRODUCTION
It is known that stained furniture can show dramatic fading, particularly when organic colorants are used. Often the fading is so severe that knowledge of the original appearance is completely lost, and in many cases the museum audience is not even aware of the fact that the wooden objects once looked different. Even for professionals it can be a surprise, as was the case with a piece of furniture designed by Piet Kramer in 1915 now in the collection of the Cultural Heritage Agency of the Netherlands (fig. 1).

This “bureau de ministre” had a dark-brown color that seemed to have the original stain applied. However, when dismantled by Ron Kievits during a conservation research project (Kievits 2003), it became clear that the now dark-brown color originally had a different color because a violet stain was discovered in the areas protected by light. Chemical analysis, using high-performance liquid chromatography (HPLC) coupled with photodiode array detection (HPLC-PDA) revealed that methyl violet was used. Methyl violet (C.I. Basic violet 1, C.I. no 42535 [Society of Dyers and Colourists (Colour Index) 1971]) is a synthetic colorant, developed in 1861 by Lauth and brought to the market in 1866. This dye belongs to the triphenylmethane dye class and is known as a basic dye used as textile dye, drawing ink, and furniture stain. It usually consists of a mixture of dyes. The main components are tetra-, penta- and hexa-methylated pararosaniline, although many other side products can also be present. Other furniture pieces designed by Piet Kramer in the early 20th century were stained using diamond green, nigrosine, tartrazine, orange GG, cochineal red A, and an unknown ponceau dye, all synthetic dyes from different dye classes (van Bommel 2001, 2003, 2004). Based on the chemical analysis, a wide color palette seems to have been used by Piet Kramer.

The use of synthetic colorants started in the 19th century, after the invention of Mauveine by Perkin in 1856, which is recognized as the start of high-volume production of many vivid dyes. In research dedicated to secondary marquetry (i.e., inlays applied in the 19th and early 20th centuries in objects originally created in the 17th and 18th centuries), many synthetic dyes were found, such as Victoria blue R, Fuchsine, Flavazine L., and the semisynthetic dye picric acid (Boonstra, Brujs, and van Bommel 2007). The identification of these synthetic dyes was strong scientific evidence for the hypothesis that the marquetry indeed dated much later than the original furniture. In that group of objects, only a redwood dye was found to be applied as natural colorant. Natural dyes were often used as well, as shown in a commode designed by Andries Bongen, now in possession of the Amsterdam Museum (fig. 2).

Chemical analysis, x-ray fluorescence (XRF) performed by Dr. Han Neevel, and HPLC-PDA performed by the authors showed that cochineal, madder, redwood, indigo, and an unknown dye source containing emodin as the main dye were used. In addition, the semisynthetic dye indigo carmine was identified. These results showed that a wide range of natural, and later synthetic, colorants were used. However, the objects showed that most of these colors were heavily faded, not to say completely disappeared. As a result, the objects now look different than originally intended and, as a result, cannot be fully appreciated. Based on the chemical analysis, an indication can be given about their original colors. However, it is impossible to determine what the actual colors were based on chemical analysis alone. Therefore we created mock-up samples to determine what colors can be achieved using organic colorants.

2. RECONSTRUCTIONS BASED ON HISTORICAL RECIPES
Within the framework of this research we decided to concentrate on reconstructions using synthetic colorants. An excellent overview of using natural colorants is provided by Michaelsen and Buchholz (2006). Because of the limited information in this publication regarding synthetic dyes, we decided to focus on that aspect. Studying historical recipes can be a challenging task. In particular, recipes from the earlier dates are difficult to interpret as they are often incomplete, written by observers rather than practitioners such as dyers and wood manufacturers, and...
recipes sometimes contain secret or implicit information (Kirby, van Bommel, and Verhecken 2014). Obviously, oral communication and training in the workshop was the method of knowledge transfer. However, in the 19th and 20th century this approach changed. On the one hand, recipes became easier owing to the introduction of synthetic dyes; on other hand, recording of these recipes was improved. On some occasions, dyes were accompanied by recipes when shipped to customers. We decided to study several historical sources. An interesting source, already mentioned, was the publication by Michaelsen and Buchholz (2006) that contains many transcriptions of staining with natural colors and an interesting overview of the use of synthetic dyes. We also studied a Dutch publication by van Hoek, which was focused especially on the coloring and surface treatment of wood (van Hoek 1953). Another source studied was supplied by a dye manufacturer, BASF, which showed that dye producers were keen to share this information so that the dyes sold could be used (BASF, early 20th century). We also researched a practical handbook by Turck (1899) and an Italian publication by Turco (1985) containing a transcription of staining with early synthetic dyes.

Our goal was not to achieve a complete overview of recipes within these researched publications; we were mainly interested in understanding the most relevant parameters in the recipe that affect the overall color. In a recipe, many parameters can play a role, such as the solvent to be used, method of application, working temperature, and concentration of the dye. Thus, rather than being exact, we decided to combine parameters from different recipes to create a standard laboratory recipe. This approach obviously differs from the goal to be historically accurate (Carlyle 2006), but it can be used to determine which parameters have a strong effect on the overall color and those with only a subtle effect. It is important to realize that in the actual application, one could obviously adapt the recipe during the staining process to obtain the right shade and hue, which could be a very iterative process. The recipe developed is as such not a recipe that is actually used; it can be considered an eclectic laboratory recipe. The research is extensively described elsewhere (Bommel and Fantini 2013). An overview follows next.

In the production of colored wood using synthetic dyes, it is important to pre-wet the wood to ensure an even distribution of the colorants and to make certain that the wood does not deform. Pre-wetting can be done with water, but ammonia or salt solutions also were used to improve the penetration of the dyes. The dyes first need to be dissolved, which could be done in water, but ethanol (or a mixture of ethanol and water) was used as well. Dyes from different dye classes that can interact in different ways with the wood were used. The concentrations of the dyes appear to have a strong effect on the overall color, but the method of application is also relevant. Large pieces of wood could be stained using a brush or sponge, but small pieces such as marquetry could be simply dipped into the stain, which results in a strong, even color. Dipping time or number of brush/sponge strokes also affects the color. Variations in the parameters...
The described earlier could lead to numerous reconstructions, particularly when these variations are combined. For example, if 8 parameters play a role in the staining procedure and 2 values are used for each parameter, 2 to the power of 8 reconstructions are possible (i.e., 256 mock-ups should be made). If for each parameter 3 possibilities are investigated and combined with each other, there are 3 to the power of 8 reconstructions (i.e., 6561). Because this is an impossible task, we decided to use the laboratory recipe as standard and vary one parameter at a time, with either two or three values. See table 1 for the recipes used.

We focused on methyl violet because we had already found this basic dye in furniture and ponceau 2R (CI name acid red 26, CI no. 16150); this dye is representative for acidic azo dyes, a frequently used dye class. The results are described in detail elsewhere (van Bommel and Fantini 2013); figure 3 presents one example to demonstrate the relevance of this research.

Figure 3 shows the colors obtained by dipping with methyl violet and ponceau 2R on both oak and maple, respectively. The dye concentration and dipping time were kept the same for each reconstruction, but different additives were introduced into the dye bath. As this figure shows, the addition of aluminum sulfate or acetic acid when using methyl violet had little effect on the color obtained using oak or maple wood. However, when ammonia was added to the dye bath, a slightly darker color was obtained when applied to maple and a very pale color on oak. One could even argue that the staining of oak showed a very poor result when using ammonia. This can be explained by the nature of the dye used; methyl violet is a basic dye that strongly interacts with the (slightly) acidic wood. When ammonia is added it is possible that ammonia and methyl violet compete in the interaction of the wood. Because oak is more acidic than maple, this could also explain the color difference obtained on the different wood species.

When ponceau 2R was applied using different additives, a strong increase in intensity was observed, particularly when aluminum sulfate and acetic acid was used. Use of ammonia showed a different color as well; in particular, the grain of the oak wood became more visible. The effects of the other parameters are not discussed in detail here. A very important parameter, however, is the concentration of the dye solution. Figure 4 presents the...
### Table 1: The Parameters in the Recipes and Associated Variables

<table>
<thead>
<tr>
<th>No.</th>
<th>Parameter</th>
<th>Variable 1</th>
<th>Variable 2</th>
<th>Variable 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wood species</td>
<td>Oak</td>
<td>Maple</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Pre-wetting</td>
<td>Water</td>
<td>5% ammonia</td>
<td>100 g/L common salt (sodium chloride) in water</td>
</tr>
<tr>
<td>3</td>
<td>Dye</td>
<td>Acid dye, Ponceau 2R</td>
<td>Basic dye, methyl violet</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Solvent</td>
<td>Water</td>
<td>20% ethanol in water</td>
<td>100% ethanol</td>
</tr>
<tr>
<td>5a</td>
<td>Concentration dye, dipping method</td>
<td>1.0 g/L acid dye</td>
<td>0.1 g/L basic dye</td>
<td></td>
</tr>
<tr>
<td>5b</td>
<td>Concentration dye, sponge method</td>
<td>Range of 1.0 to 15 g/L acid dyes</td>
<td>Range of 0.1 to 5 g/L basic dyes</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Additives to the dye bath</td>
<td>No additives or ammonia for acid and basic dye</td>
<td>Aluminum sulfate for acid dyes</td>
<td>Acetic acid for basic dyes</td>
</tr>
<tr>
<td>7</td>
<td>Temperature</td>
<td>90°C aqueous solution</td>
<td>70°C for 20% or 100% ethanol</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Method</td>
<td>Dipping in dye bath</td>
<td>Apply directly with a sponge</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Duration</td>
<td>Dipping: 15 minutes</td>
<td>Dipping: 30 minutes</td>
<td>Sponge: As fast as possible</td>
</tr>
<tr>
<td>10</td>
<td>Cool dye bath with wood inserted (dipping only)</td>
<td>1 hour</td>
<td>2 hours</td>
<td></td>
</tr>
</tbody>
</table>

*From Bommel and Fantini (2013).*

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**Fig. 3.** Effect of different additives on the color of methyl violet and Ponceau 2R applied on oak and maple.
effect of the concentration on the color of the wood. As can be seen from this figure, the colors obtained could be very strong, giving a vivid appearance to cultural heritage objects.

3. DEGRADATION RESEARCH
Despite the very strong and brilliant colors obtained, the synthetic dyes are known to fade rapidly depending on their chemical nature. The Colour Index lists fastness properties for many of these dyes when applied on different textiles, such as wool, silk, cotton, or linen, including the light fastness properties (Society of Dyers and Colourists [Colour Index] 1971). Because these properties are dependent on the substrate, a short research project was conducted by applying some synthetic colorants on wood. The work was done by Jettie Timmer in the framework of her master’s thesis at the Conservation and Restoration of Cultural Heritage Department of the University of Amsterdam, in collaboration with Frank Ligterink, senior scientist at the Cultural Heritage Agency of the Netherlands. Four different dyes were applied to wood; methyl violet, ponceau 2R, diamond green G, and nigrosine. All of these dyes are found on pieces of furniture designed by Piet Kramer. The dyes were applied to oak and elm, woods often used by Kramer. The standard recipes described in the previous section were used and two different finishing layers (i.e., beeswax and shellac) were applied as this could affect the fading. Part of the stained wood was exposed to light without any finishing layer for comparison. Aging was achieved with Atlas Xenotest Alpha High Energy equipment following the ISO 105-B02 standard. The light dose was calculated to be compared with “museum years” at 200 lux, in daylight through glass. By covering parts of the wood with aluminum foil, a step-by-step exposure could be created, resulting in a range of discolored patches. Color measurements were done by scanning the aged mock-ups using a flatbed scanner and measuring laboratory values using Photoshop, which were used to calculate the color difference in delta-E(dE). The use of Photoshop allowed us to measure several small areas (1.3 × 1.3 mm) and calculate the average color without interference from the wood grain. A typical result is presented in figure 5; the research is discussed in detail elsewhere (Timmer and van Bommel 2015).

With this framework, it is clear that a color difference can be observed for methyl violet and diamond green G after an equivalent of 1- or 2-year exposure in museum conditions; after an equivalent of 5 years, the colors are almost gone. Ponceau 2R is more stable, showing severe fading after 10 years and almost complete fading after 40 years. Nigrosine, on the other hand, seems to be very stable. Although we expected strong discoloration, we were still surprised that it happened so fast. This means that after a couple of years of exposure in a museum or a house, for which these objects were originally designed, the color would be completely gone. This obviously raises the question as to how the owners of the objects dealt with this issue and whether new stains, maybe even with a different color, were applied. Extensive degradation research was done on methyl violet, revealing the degradation mechanism in solution that could help determine the state of degradation, but this requires more in-depth research (Confortin et al. 2010).
4. RETOUCHING WITH COLORED LIGHT

The strong discoloration observed obviously has a large impact in the appreciation of the objects. As mentioned in the introduction, knowledge of the original appearance had been lost; in particular, the museum audience is often not even aware of the fact that objects at one time showed very vivid colors. It is obviously possible to obtain a better idea of the color applied, based on chemical analysis, the reconstructions made, and degradation research performed as described earlier, but it is quite difficult to determine the exact color. Even then, from an ethical point of view, it would be a big step to apply new stains on pieces of furniture. Not only is this rather invasive because the stains will penetrate the wood and cannot be removed easily, but it also makes it complicated to adapt the color if later research indicates a different hue. Restoration should be reversible unless no alternative exists. But this alternative does exist—one can decide to “retouch” the object with colored light. A color observed is always dependent on the color of the light applied, the part of the visible spectrum reflected, and the eye of the observer. Thus a different appearance can be obtained by adapting the color of the light used to illuminate an object.

To our best knowledge, the first to apply this concept was Lafontaine, who used colored filters to compensate for a yellowed varnish (Lafontaine 1986). Lafontaine’s goal was to get a better idea of what the effect of removing a yellow varnish from a painting would be before the varnish was actually removed. Varnishes are known to be yellowing; Lafontaine considered this a “yellow filter” on top of the actual painting. The yellowed varnish reduces the reflection of the light, particularly in the blue and violet regions of the visible spectrum. This can be compensated for by adding more blue and violet light to the illuminating source such that the yellow of the varnish disappears, at least for the human eye. Lafontaine used a slide projector and examined several filters, first on a test panel with a range of colors present underneath an artificial yellowed varnish. Part of this painting was not covered by the yellowed varnish and acted as reference. By testing several filters and varying the intensity of the light source, he was able to obtain a good visual effect. In his opinion, this could be helpful for the conservator in the decision-making process regarding if and to what extend the varnish should be removed. He suggested that it would also be an interesting tool in the exhibition room if no varnish removal was possible for whatever reason.

Fig. 5. Degradation of several dyes accelerated aged by light. Image from Jettie Timmer.

<table>
<thead>
<tr>
<th></th>
<th>Methyl violet</th>
<th>Ponceau G</th>
<th>Diamond green</th>
<th>Nigrosine</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>referentie</td>
<td>referentie</td>
<td>referentie</td>
<td>referentie</td>
</tr>
<tr>
<td>0,5 year</td>
<td>BWS 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 year</td>
<td>BWS 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 year</td>
<td>BWS 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 year</td>
<td>BWS 4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 year</td>
<td>BWS 5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 year</td>
<td>BWS 6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40 year</td>
<td>BWS 7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>80 year*</td>
<td>BWS 8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*museum year, 200 lux
This idea is studied further by Stigter, who to our knowledge was the first to apply colored light in an exhibition room to compensate for color changes in an object (Stigter 2004). She studied several works by van Elk, one of them a wall sculpture entitled Roquebrune (1979, Frans Hals museum). This work, a three-dimensional triangle, consists of acrylic paint on the left side and a photograph mirroring the paint on the right side. Obviously, the balance in color is quite important, but unfortunately the photograph was severely discolored. Because the yellow dye in the photograph faded and only a small amount of cyan colorant was present, the overall appearance of the photograph was magenta. To compensate for the magenta, a light-green filter was applied because this is absorbed by magenta and therefore not reflected. A second, straw-tinted filter was applied by the author to compensate for the faded yellow. The overall effect was quite positive, as confirmed by the artist van Elk.

The application of colored filters with a single color, as noted in the two previous examples, obviously limits the possibility when several colors are retouched at the same time and when structures are complicated. Therefore computerized illumination via a beamer is a good alternative, as demonstrated by Perkins (Perkins et al. 2011). They studied 500-year-old tapestries and “virtually restored” one of the Henry VIII Story of Abraham tapestries (commissioned in 1537, Royal Collection at Hampton Court Palace) for exhibition purposes. As with furniture, textiles are known to fade heavily under the influence of light. A good impression could be obtained of the original color by chemical analysis of the dyes and mordants used, creating reconstructions based on historical recipes and measuring the colors of yarns protected from light. Using computer software and a beamer, the faded colors were illuminated with light. With this approach, multiple colors could be “retouched” with relatively high resolution. By manipulating this image, visitors could not only have an impression of the original color but they also saw how the tapestry would have looked after 100, 200, 300, and 400 years of aging, based on artificial aging studies.

The approach described by Perkins et al. (2011) was similar to the approach within our research. Chemical analysis was done to identify the colorants present; based on historical recipes, reconstructions were made and artificially aged. Our color measurements of parts of the object protected from light provided an overall idea of the original color applied. Although we believe that this approach will get us as close as possible to the original color, this methodology is not always feasible. Therefore it good to note the research recently done by Stenger et al. (2016) using old photographic images to determine the color of wall paintings by Mark Rothko. Similar to the approach by Perkins et al. and our own approach, they used a computer and a beamer to achieve a high-resolution retouching.

4.1 Case Study 1: Retouching a Cabinet Designed by Kramer

Amsterdam School furniture is often characterized by expressive organic and voluminous decoration; yet, within this study, we investigated a late Amsterdam School buffet made between 1933 and 1936 by Piet Kramer that is much more sober in design and decoration (fig. 6).

Originally, the bright monochrome orange color of the piece—achieved by the use of synthetic dyes—gave the buffet an expressive appearance. This bright color can still be found on the interior and some exterior parts of the buffet that were not exposed or barely exposed to light; on the rest of the exterior only a slight shade of orange can be detected. Because of the discoloration, the color of the oak substrate is predominant (fig. 7), but it is important to realize that the oak also has darkened over time.

Previous research on the buffet proved that the discolored orange dye was original and not the result of the application of
a new stain (Groeneveld 2014). To understand its original appearance, small samples were taken from light-protected areas and analyzed using HPLC-PDA. Results showed that the dye was composed of 53.7% tartrazine, 38.5% orange GG, 5.3% cochineal red A, and 2.5% of a Ponceau-type dye. Next, reconstructions were made in which this same proportion of colorants was used. Although the proportions were known, it was not possible to determine the absolute amount of dyes present as this requires laborious calibrations of the analytical system and, more importantly, several samples are necessary to obtain a good overall impression. Therefore the stains were applied in different concentrations but with the same relative amounts as found in the sample. A concentration of 15 g/L created a similar orange color as that visible on the interior of the buffet (Groeneveld 2014). Because some synthetic colorants discolored quicker than others, even when not exposed to light, the original proportion might differ from the measured proportion, as completely discolored colorants will not be detected (Timmer and van Bommel 2015). Therefore the exact color applied remains unknown. However, based on chemical analysis, the reconstructions made, and the color observed in light-protected areas, we believe that we can arrive close to the original intention. Therefore we used the color observed on the interior of the right door as the provisional goal for retouching with colored light (fig. 7). The inside of the door was selected as it provides a nice homogeneous and large surface. The substrate is oak, just like the outside of the buffet, while the inside is also made up of pine. The buffet shows a heterogeneous discoloration; by retouching with light the goal was to obtain a more homogeneous appearance, closer to the original. The different shades in the oak substrate are corrected as they add to the patina.

The retouching with colored light was achieved with a computer equipped with projection-mapping software connected to beamers. Two standard presentation beamers (Epson EB-S9) from the University of Amsterdam were available for use. Using two beamers allowed us to project from two sides—one beamer for the front of the buffet and one for the left side. To avoid disturbing reflection of the light, the beamers were placed under an angle at 2.10-m height and 3.9 m away from the buffet. The room in which the buffet was placed was lit with little natural light (measured as a light intensity of ~30 lux). Video Projection Tools 7 (VPT 7), a free downloadable projection-mapping program, was selected to control the beamers. VPT 7 is easy to use; shapes can be made that serve as masks projected on the cabinet and color, expressed in RGB values, can be assigned to these shapes. The areas that should not be retouched with colored
light, such as the background and the interior of the right door when opened, were illuminated using white light.

Because our perception is influenced by both the reflection spectrum of the object and the spectrum of the light, the following statement can be made: the perception of the bright-orange reference color illuminated with white light should be identical to the discolored exterior of the buffet illuminated with colored light. To determine the color of the light projected, it was necessary to quantify the discoloration. Normally, color measurements are done with photo spectrometers that measure small spots. However, because the wood itself does not show a homogeneous color, the complete object was illuminated with light with an RGB value of 0.75 on an arithmetic scale of 1. This white light was considered to be of a pleasant intensity and hue. A photograph was taken and used to perform the digital color measurements on the Digital Color Meter program from Apple. The program was set to measure the average color of four pixels. Twenty measurements, expressed in arithmetic RGB values, were taken of the interior of the right door. Because the oak of the exterior of the buffet was less homogeneous than the interior of the door, 50 measurements were taken to measure the color of the discolored exterior. An average (a highest and lowest RGB value) was determined for both the reference color and the discolored color.

As previously stated, our perception is influenced by both the spectrum of the light and the reflection spectrum of the object. Therefore the following equation can be constructed:

\[
\text{Perception} = \text{RGB value light} \times \text{RGB value object}
\]

Because the goal is to make the perception of discolored parts of the buffet equal to the reference color, it can be stated that

\[
\text{Perception} = \frac{\text{RGB value reference color}}{\text{RGB value discolored parts of the buffet}}
\]

The RGB values of the white light, set through VPT 7, are known in addition to the reference color and the discolored parts of the buffet (after conducting color measurements). Therefore this equation can be used to calculate the color of the colored light:

\[
\text{RGB value colored light} = \frac{\text{RGB value white light}}{\text{RGB value reference color}} \times \text{RGB value discolored parts object}
\]

A range for the RGB value of the colored light was determined by performing the calculations with the average, highest, and lowest measured RGB values. These calculations and the formulas used were developed by Frank Ligterink, senior scientist at the Cultural Heritage Agency of the Netherlands. These ranges were as follows: R range = 0.72 to 0.87; G range = 0.20 to 0.50; and B range = 0.67 to 0.83. Unfortunately, these ranges are quite large, which means that reliance on visual analyses at this stage is unreliable.

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Using the projection-mapping software program was straightforward. Masks were created in VPT 7 and projected by the beamers. When the beamers were set in focus, a slight grid pattern—basically the pixels of the projector—was visible from up close. By setting the beamer slightly out of focus, this pattern was no longer visible. The shapes were fine-tuned during projection so that they precisely covered the discolored exterior.

The background and reference color were illuminated with the same RGB value of 0.75, which was also used during color measurements. Within the calculated range a RGB value of 0.87, 0.45, and 0.6, respectively, was determined through visual analyses to be a good match to the reference color. The range—while quite large—was a helpful tool, as a good color match was selected quickly. Although variations in the color of the oak were not corrected, the difference in the colors on the left side of the buffet, which was the result of partial shading from light, was corrected by projecting a slightly different RGB value onto it. The result is shown in figure 8.

The result was evaluated through both measurements and qualitative perception research. Digital color measurements were made on a photograph taken of the result obtained. Ten measurements on both the reference color illuminated with white light and the discolored parts illuminated with colored light were carried out. The average RGB values of 131.9, 29.8, and 20.9 of the reference color and average RGB values of 138, 32.8, and 22.4 of the recolored exterior proved that a good color match was achieved. Lux measurements were taken to determine whether the result met guidelines for museum lighting (Brokerhof 2005). The colored light had a light intensity of 140 lux, which was
found to be acceptable. The colored light, projected onto the buffet, is reflected and discoloration under the influence of light is mainly the result of absorption of light, not what is reflected.

The result was also evaluated by asking a group of 10 conservation scientists, curators, and conservators of the Cultural Heritage Agency and the University of Amsterdam to answer a questionnaire with 7 questions (van Adrichem et al. 2015). Questions focused on determining whether the result was experienced as realistic and whether a difference in color between the reference color and recolored parts and a difference in color through light or through staining was observed. The responses were very positive. The result was considered highly realistic and the patina was kept. The orange colors were found to be identical. Light imitated the qualities of a dye very well, as it achieved the same transparency. A conservator wrote the following: "As a whole it gives a natural and balanced appearance. The difference between the more discolored and well preserved parts is equalised to a degree that gives a 'rustig beeld' [calm image] whilst preserving local variations that prevent 'overkill' and give a natural effect."

Because the result was considered to be very satisfactory, more objects from the ensemble in the collection of the Dutch Heritage Agency were recolored by projecting colored light onto them as part of a test exhibition at Bijzondere Collecties in Amsterdam (figs. 9 and 10).

4.2 CASE STUDY 2: RETOUCHING AN 18TH-CENTURY COMMODE BY BONGEN

To investigate the possibilities of retouching with light even further, an 18th-century commode signed by Andries Bongen was used as a second case study (van Adrichem and van Bommel 2016). Whereas the cabinet from Kramer had one color and a simple, straightforward design, the commode by Bongen represents almost the complete opposite. First, the overall shape of the commode is curved, which challenged the projection. Second, we were mainly interested in restoring the colors of the completely faded marquetry showing a vase with multiple-colored flowers and leaves. Obviously, this design is very complex and detailed. Rather than illuminating large squares with a single color, small flowers, leaves, and stems had to be retouched using a wide range of colors. The marquetry is presented on a fond made of purpleheart wood and the borders of the front are made of tulipwood veneer separated from the purpleheart veneer by a small strip of holly. These parts of the commode were not stained; it therefore shows its natural color but these parts have severely changed over time. The marquetry is stained using natural and semisynthetic colorants presented in table 2.

In this part of the research, no reconstructions were made as our main aim was to determine if we could project colored light onto the commode at such a detailed level. To ensure that the object is in balance, not only the marquetry but also the purpleheart, tulipwood, and holly are retouched with colored light. Interestingly, these colors are relatively easy to determine because we could use fresh wood as reference. The marquetry color was more complicated because, even though most of the colorants were identified, the concentration was so low that the actual
color could not be determined. We therefore decided to contact Dr. Sam Segal, a botanist, who was able to identify the flowers depicted. Because marquetry artists aimed for realism in the 18th century, we decided to retouch the flowers based on the natural colors expected. For an accurate color reconstruction, more research was required.

In this case study, only one beamer was used and we decided to illuminate the front of the object, leaving both sides showing the present color. The commode was set up in an exhibition room of the Amsterdam Museum and the projector was positioned at a height of 10 cm from the floor. Because of the shape of the object and the details required to illuminate the marquetry, photogrammetry was performed by Sander Mettes using Agisoft PhotoScan. This resulted in an image with a very high texture resolution—at the level that fine details, including the grain of the wood, were visible in the scan. Next, masks were made for each individual part (the flowers, leaves, branches, butterfly, and vase). In addition, masks were made for the unstained purpleheart, holly, and tulipwood because these needed to be retouched as well. Special attention was paid to the tulipwood. Although it currently shows a rather monochrome color, it was originally applied with more contrast because tulipwood shows a straw-colored background and pink streaks. This was included in the projection. All the different masks could be combined in one image; each mask was assigned with the required RGB value using Photoshop.

Because of the complexity of the image, VPT 7 could not be used for this object. We decided to work with Resolume Arena 5 Media Server software instead, which had a more accurate and detailed project-mapping function. The result of the final projection is illustrated in figure 11.

During the exhibition in the museum, a loop of three files was programmed showing the object with white light, with the warped colored image, and applying no light (museum lighting only) with time frames of 30 seconds. This loop was then placed on a Secure Digital (SD) card and put in a BrightSign UDP player to control the beamer. Figures 12 and 14 show the result of the final projection.
of the illumination of the commode using colored light, while in figure 2 and 13 the commode is shown using white light.

The result was evaluated by visual analysis and light intensity measurements were also done (results presented in van Adrichem and van Bommel [2016]). The main goal of the visual analysis was to determine the accuracy of the positioning of the colored projection and whether the result was a realistic impression. In the first case study, we used beamers that were slightly out of focus to avoid the visibility of the grid. However, in the illumination of the Bongen commode, out-of-focus projection was not possible owing to the high-precision illumination that was required. This means that a high-resolution beamer is preferably used; with the present beamer the grid was slightly visible at close range, but from a distance of 1.5 m the grid pattern was not distracting. The high precision required also means that the position of the beamer and the object should remain exactly the same during illumination; a slight change of position immediately showed a large distortion of the projected images. For that reason, the beamer was installed in a small, very stable box.

Because the beamer was positioned just 10 cm from the floor, the light projected was reflected in an upper direction that resulted in an almost white reflection spot in the center of the object. This problem could be avoided by looking at the object from a different direction (as seen in fig. 14). This also clearly indicated that the position of the beamer should be considered as well. Mounting the beamer at the ceiling would give a better result but was not possible in the exhibition room available.

The overall result looks very promising, and the retouching of the natural colored wood was quite realistic. For these areas, fresh wood was compared as a reference and indeed showed a very similar appearance. This was less so for the vase, butterfly, flowers, leaves, and branches because we did not have any reference color as reconstructions were not yet made. The projection mapping could be done very accurately, but more research is needed to establish the original color of these parts. However, when this information is revealed, it is relatively easy to adjust the RGB values of these parts. The gilded mounts were illuminated with a slightly grayish color because bright white light was thought to give an exaggerated appearance. However, the warm gold appearance that the mount normally shows was lost, thus this color needs to be adjusted in the future. Using one projector had the disadvantage that shadows of the mounts were created on the...
wood, which resulted in a partly not retouched surface. Using two beamers, as was done in the first case study, could overcome this problem. Although improvements certainly can be made, we were very satisfied with the result and the commode was on exhibition in the Amsterdam Museum for more than 6 months, affording the audience the bright color it once had.

5. CONCLUSIONS AND FUTURE PERSPECTIVES
In this review article we hoped to provide an overview of the possibilities for understanding faded objects. In our opinion, the combination of chemical analysis, reconstruction based on historical recipes, degradation research, and retouching objects with colored light revealed much information and generated new knowledge. The projection of colored light on objects is not only a very powerful educational tool, suitable for showing the outcome of scientific results to a wider audience, it is also a research tool in itself. The tool can bridge the gap between scientists and art historians and conservators. By discussing the results based solely on scientific knowledge, in front of the illuminated object, gaps in knowledge can be ascertained. Although chemical analysis is certainly possible, determining the original colors by this method remains very complicated, even when reconstructions are made. Input from art historians is required to improve our understanding of the colors used. Because altering the RGB values of the projected light is very simple, the values can easily be adapted when new knowledge is obtained. In principle, it is even possible to create different images based on different information. A projection based purely on scientific information might be too one-dimensional, but a second image can be generated based on the knowledge of the art historian and a third image can be generated based on the knowledge of the conservator and comparing these three.

Nevertheless, there is room for improvement in retouching objects with colored light. Shadows and unwanted reflections can be diminished by using multiple beamers. The accuracy of the beamers determines the accuracy of the image obtained. It would be interesting to also improve the visibility of engravings and other details using projected light. Aside from the faded colorants, it is also relevant to study the natural discoloration of the wood, with and without colorants present.

The perception of the audience is an aspect not yet covered. A detailed visitors’ study was not part of this research, but short inquiries showed that many museum visitors liked the retouching in color or thought they were recently stained. Although this is very promising news for retouching with colored light, based on extensive research it is obviously not the intention to mislead visitors. Therefore when this technology is applied, a good explanation should be given and one could consider including loops, as was done for the Bongen commode, which was presented in both normal light and colored light.

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SOURCES OF MATERIALS

Agisoft PhotoScan
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Atlas Xenotest Alpha High Energy
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END NOTE
1. In 2015 we exhibited a nightstand and chair for 4 months at the museum, called Bijzondere Collecties, of the University of Amsterdam. Museum visitors could complete a short questionnaire. Most people experienced the result as realistic.

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MAARTEN R. VAN BOMMEL has been a professor of conservation science at the University of Amsterdam (UvA) since 2015, where he holds a position at the Faculty of Humanities and the Faculty of Science. This multidisciplinary position is rather unique within the UvA. He is chair of the section on conservation and restoration of cultural heritage, where future conservators/restorers are trained within 9 different object-related tracks. The technical art history track is also part of this group. After studying analytical chemistry at the UvA, he received a PhD at Leiden University in 2002. He worked as senior scientist at the cultural heritage agency of the Netherlands (RCE). He was involved in important research projects, such as...
the history and making of the Victory Boogie Woogie by Piet Mondrian, research on prehistoric dyeing techniques, indoor air quality, and numerous small- and large-scale research projects dedicated to organic colorants. He has acted as work package leader in several European-funded projects, currently for IPERION-CH (Integrated Platform for the European Research Infrastructure on Cultural Heritage). His main research now focuses on the identification and degradation studies of natural and synthetic dyes and organic pigments, with the goal of determining the original appearance of objects of art. This interdisciplinary research includes analysis, the study of historical recipes with the aim of doing reconstructions, degradation research on different materials, and the characterization of degradation products and retouching with light—a promising fully reversible retouching technique that works especially well on furniture. He is one of the leading experts in dye and organic pigment characterization, both of natural and synthetic origin. Address: Johannes Vermeerplein 1, 1071 DV Amsterdam, the Netherlands. E-mail: M.R.vanBommel@uva.nl.

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