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Insight into Canvas Paintings' Stability and the Influence of Structural Conservation Treatments

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ABSTRACT. Materials science has proven useful when designing conservation solutions since it provides a broader understanding of the properties and behavior of single materials (artists' and conservation materials) as well as their interaction with each other in a composite painted structure. Early on, it was recognized that this approach would be useful for research in conservation methods and materials. Adding or removing materials through conservation intervention inevitably changes the structure and properties of an object and thereby changes the way it responds to external stimuli. Studies have shown that some of the treatments applied by paintings conservators will change the way that objects perform in time, especially the way they respond to changes in temperature and/or relative humidity. Use of adhesives (i.e., consolidation of paint, mending cracks, etc.), a more substantial addition of materials (i.e., lining, filling lacunae, etc.), or simply replacing a varnish can lead to significant change in the painting structure and properties and, consequently, the way the new composite ages in different climates. Understanding the structural behavior of painting materials is therefore crucial to the design of conservation strategies that support long-term preservation. This paper presents insights into the current knowledge on the changes induced by selected conservation treatments and the consequences of adding or removing material. The aim is to reflect on options for designing conservation treatments that are both interventive and preventive, rendering the painting equally or more able to tolerate climate fluctuations than before treatment.

INTRODUCTION

Treatments performed by conservators in day-to-day practice often change the structure of the treated object, thus affecting its response to changes in temperature or relative humidity (RH) as well as its performance over time. With best intentions, conservators have traditionally added materials like wax, glues, and resins or removed materials from previous interventions. Materials were, in many cases, restrained or tensioned, resulting in increased stress levels to the original material. It is therefore important to have a better sense of the specific consequences that conservation treatments may have on the objects in both the near and the far future.

In order to select treatments that consider the long-term effects, it is important to know the relevant ambient climate, moisture and temperature swelling coefficients of original and added materials, and to be aware of the changes in structure and mechanical properties that each treatment causes. The study of the mechanical and dimensional properties of objects and conservation materials provides a

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tangible way to understand the behavior and the structural consequences of conservation choices.

This paper will discuss results obtained by research into structural and mechanical behavior of treated paintings and the impact that treatment has on the stability of paintings. This paper furthermore proposes a three-step approach to structural conservation that will integrate consideration for structural changes into the conservation decision-making process. The focus is on paintings, but the materials science approach can be used widely for other objects and represents a fundamental method to comprehend the challenges that conservators face (Fuster-López and Andersen, 2014).

THE MATERIALS SCIENCE APPROACH IN CONSERVATION

Conservation can change an object. In order to understand this change one must understand the object from a materials science point of view. The discipline of materials science was defined as a function of four essential components by the American engineer William D. Callister: processing, structure, properties, and function (Callister, 2007:4).

In terms of materials' performance, these components are a good starting point for cultural heritage as well. The question is, What happens once degradation sets in and is followed by a conservation treatment where structure, properties, and performance can be changed in various ways? The local climate surrounding the object may also affect structure, properties, and performance significantly (Figure 1).

Early steps of using an engineering approach to paintings were taken in the beginning of the twentieth century, as described in a report from the Courtauld Institute (MacIntyre et al., 1934). This report pointed out the different responses to relative humidity of the substrate and the paint layer in a canvas painting that will "either tend to loosen the paint film from the canvas or produce cracks" (MacIntyre et al., 1934:14). This report and an article that same year from the same group of researchers (Plenderleith and Cursiter, 1934) show early examples of systematic testing of structural conservation methods through so-called endurance tests of, for example, tinfoil covering of panel paintings and a wax-resin lining of canvas paintings. These tests included rather extreme conditions like immersion of a painting in a water tank.

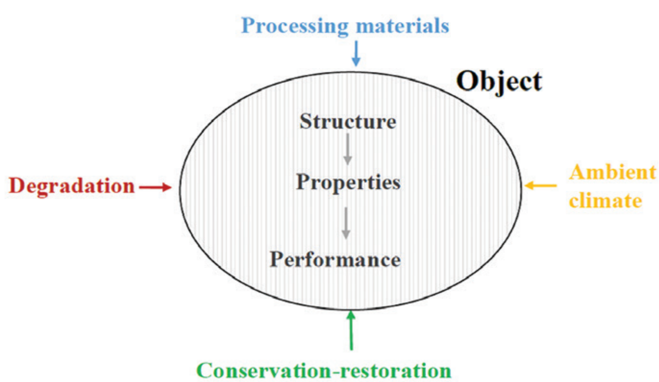

FIGURE 1. Model inspired by Callister (2007) for the interrelated concepts affecting the structure, properties, and performance of objects. After production of an object degradation process, structural conservation and ambient climate can change all three concepts and thus change the way the object looks and performs and/or degrades.

A typical article on conservation in the 1960s, 1970s, and 1980s aimed at demonstrating the usefulness or drawbacks of a certain material, method, or approach (Hacke, 1963; Berger, 1970; Mehra, 1975; Ketnath, 1976; Mecklenburg and Webster, 1977; Hedley and Villers, 1982; Fieux, 1984). Research into the effect of structural conservation thus had the nature of exchanging ideas or reviewing consequences of conservation methods based on criteria like stiffness, hygroscopicity, and reversibility. However, there was no consensus as to the optimal demands for conservation treatments like lining or consolidation. Structural all-in-one treatments like wax-resin and glue-paste linings were questioned while new methods and a consensus on long-term strategies for structural treatments were sought. With the introduction of preventive conservation approaches and the emerging field of conservation science, more research now is concerned with methods of documenting behavior in paintings rather than investigating the effect that conservation methods have. This line of approach has led to advances in our ability to predict how materials will behave in certain ambient climates, but not many advances have been made when it comes to new treatment options. Meanwhile, large structural treatments are still performed, and we are still not able to understand the full consequences of the impact that previous treatments have on paintings in our collections. The desire to keep paintings in their original historic settings—sometimes avoiding nonoriginal glazing or major structural treatments—can result in smaller interventions in which cracks are filled or paintings are retensioned without sufficient support.

New advances linked to the environmental discussion have recently been made in the investigation of deformation (Groves et al., 2007, 2008; Malowany et al., 2014; Klausmeyer et al., 2016) and moisture sorption (Hendrickx et al., 2016a, 2016b). Neither sorption nor deformation, however, is the direct course of failure in materials. Stress is the direct cause of failure, and it would therefore be useful if the above-mentioned research was complemented with research into the stress development and failure in materials at different ambient conditions. The consequences of structural conservation can then be assessed method by method.

THE STRUCTURAL IMPLICATIONS OF SOME CONSERVATION DECISIONS

Reinforcing a paneled structure, providing an additional stretchable support (i.e., lining, strip lining, etc.), mending torn fabrics, filling missing paint layers, and simply providing cohesion to powdery or flaking paint have been common practices in paintings conservation throughout history. In all these cases adhesives have been used to a greater or lesser extent and can be considered the common thread when following the history of the conservation-restoration profession. Describing the development of conservation materials and methods depends on the geographical location and climate, as well as criteria trends in this constantly evolving field.

ADHESIVES IN THE CONSERVATION OF PAINTINGS

With the early developments of the chemical industry after World War II, synthetic resins came on the market. The use of natural adhesives (glues, gums, resins, etc.) coexisted with these new technical developments (see Figure 2). The fine arts soon became flooded with synthetic paints and adhesives, and this has been a growing tendency to date. The use of suction tables and hot tables (Ruhemann, 1953; Hacke 1963; Mehra, 1975), humidification systems, and all kinds of devices were soon associated with the potential use of synthetic resins to treat powdery and flaking paint, relax stiff fabrics, and line paintings. The apparent advantages offered by the new synthetic adhesives over the natural ones favored their popularity and increased use in the field during the 1990s.

The use of adhesives has significant structural implications in painting stability since they change paintings irreversibly. It is widely known that each adhesive presents different adhesive and cohesive properties. Whereas factors such as the microstructure, surface cleanness, and roughness of a surface influence the bonding of an adhesive to a substrate, the cohesion of an adhesive results from a variety of interactions within adhesives such as chemical bonds within the polymer, cross-linking, and inter- as well as intramolecular interactions.

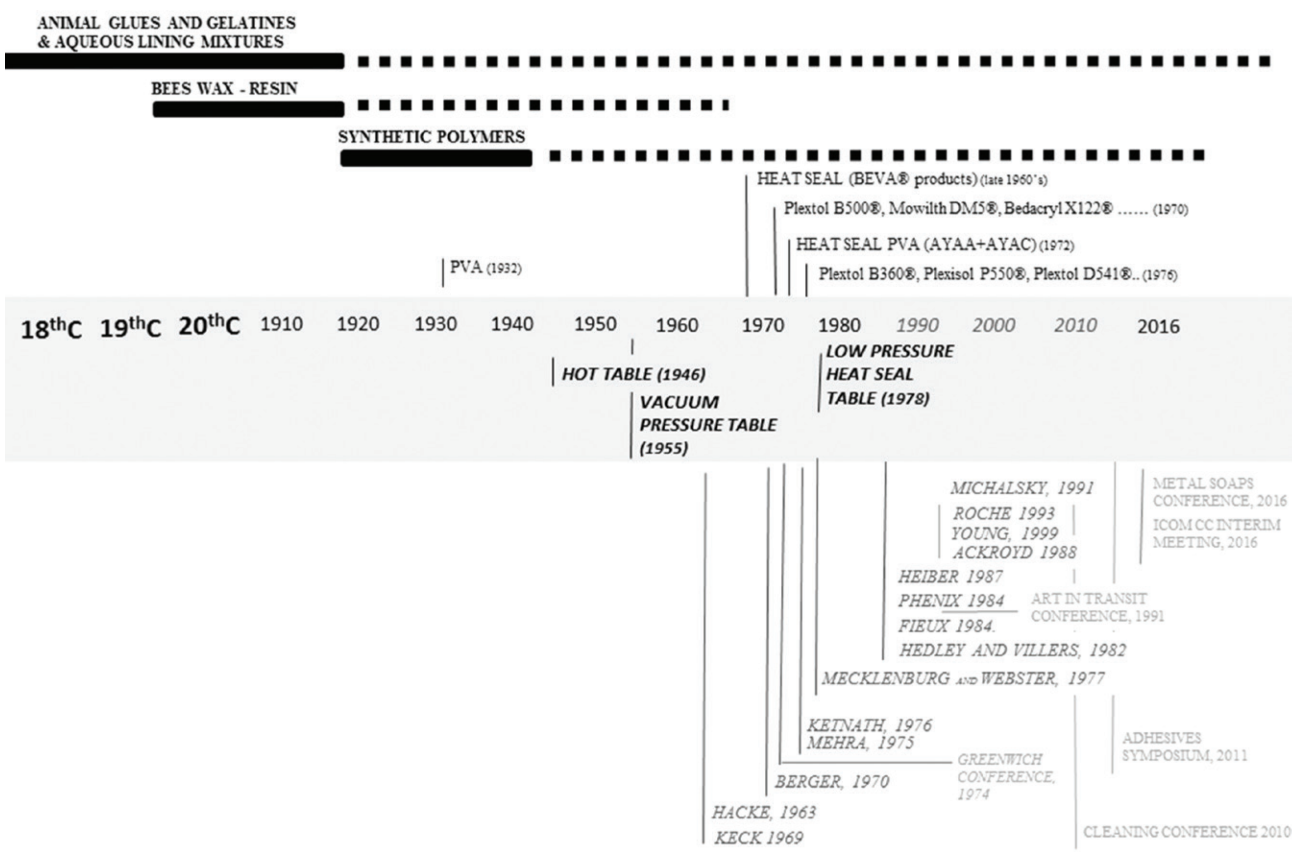

FIGURE 2. Chronology of adhesives use in the structural treatment of paintings, the invention of specific devices and equipment, and related literature and conferences.

In order to assess the performance of adhesives in commonly used solvents, 20 different adhesives in a total of 40 different solutions were recently tested in a research project by Mecklenburg et al. (2012). These adhesive solutions were chosen because they are the most common on the basis of a survey carried out in 2007 among the conservation community. Tensile, peel, and penetration tests were carried out to evaluate their adhesive and cohesive behavior as well as the extent of penetration expected for each of them for different substrates of known porosity. Results indicated that animal glues and gelatins develop high cohesive strengths and stiffness, far beyond all the synthetic polymers tested. Nevertheless, animal glues and gelatins are water sensitive and therefore prone to biodegradation and are strongly influenced by RH fluctuations, becoming brittle with low RH values and losing nearly all their cohesive strength with high RH. The same research showed that Gustav Berger's Original Formula 371 (BEVA [Berger ethylene vinyl acetate] 371) presents a very low cohesive strength, but it bonds well to certain supports. In other words, although the elastic modulus and the ultimate tensile strength are very low (0.6 MPa) at room conditions (~50% RH) compared to other adhesives such as animal glues and gelatins (±68 MPa), the peel tests (or adhesion tests) showed that its adhesive bond strength to linen and polyester substrates is higher (±6 N/cm) than the one shown by hide glue (±4.4 N/cm) or sturgeon glues (±5.5 N/cm; Mecklenburg et al., 2012). It is well known that BEVA products revolutionized the conservation community. However, the main concern today is not only the chemistry behind the adhesive mixture itself but also its long-term behavior and stability in use (Ploeger et al., 2014). The concern here relates to the fact that the BEVA adhesive has traditionally been used in various circumstances and for different needs without discriminating between the structural requirements in each case.

How can research into mechanical and dimensional properties of adhesives be related to hands-on conservation practice? For example, the results above indicate that although BEVA 371 could work well bonding different materials together (i.e., flaking paint), one cannot expect this adhesive to provide any stiffness to any painted system. For example, BEVA 371 could be an option to adhere flaking paint in a water-sensitive painted surface. However, when used as a lining adhesive, it requires the addition of a stiff auxiliary fabric or interleave (Andersen and Nielsen, 2012) to provide sufficient stiffness (and therefore support) to the canvas painting.

Another interesting issue to discuss is the role of solvents when using adhesives. The use of any adhesive usually requires the use of a vehicle or solvent intended to help the polymer penetrate the pores and reach the areas where strengthening is needed. Solvents used in adhesive solutions can be retained in the painted structure for long periods of time before complete evaporation. When monitoring the change in the mechanical properties of adhesives as a function of the evaporation time, the results indicate that the thicker the adhesive film is, the longer it takes for the solvent to evaporate. Research in the context of adhesives used in paintings conservation has also revealed that different solvents have different drying times, which impacts cohesive and adhesive properties. Fast-evaporating solvents such as acetone accelerate drying but result in extremely stiff and brittle films (Mecklenburg et al., 2012).

Since treated paintings will always be a version of what the artist created, it is essential to estimate the consequences of the conservation decisions. Following the above considerations, the design of conservation strategies must be the result of a thoroughly evaluated process in which the understanding of the material's properties in a given environment must merge with the possibilities and limitations of conservation materials and methods.

The study of materials' properties helps us understand the different adhesive and cohesive strengths of adhesives, the stiffness they present, and the fact that the strength requirements for adhesives depend on what function they are to serve. As explained above, no adhesive solves all types of problems. Different causes of damage will turn into different failure mechanisms and will have different adhesive and cohesive requirements, and therefore, different adhesives in different solvents and proportions will be needed in each case. Furthermore, many structural treatments in canvas paintings go beyond the use of adhesives. The addition of fabrics, including inserts, patches, and linings, is also common practice.

STRUCTURAL IMPLICATIONS OF LINING

A lining represents a substantial change in the structure of a painting as a significant quantity of material is added and the tension of the painting may be changed through restretching the painting. Linings can be complicated structures with interleaves, or they can be simple additions of canvas with an adhesive. A large quantity of added material will not necessarily be reflected in a large change in properties in the overall structure since this depends on the properties of the individual materials chosen for the lining task.

The materials that may be added can be divided into the following categories: lining canvas, lining adhesive, and interleaf. Each material serves a purpose, and therefore, appropriate choices have to be made to obtain the result required. Depending on materials and approaches, the lining canvas can be thought of as a material that stiffens, reinforces, or secures the original canvas, the paint layer, or the structure as a whole. The adhesive can be thought of as a material that may impregnate, stiffen, or simply attach to the original canvas or painting. The interleaf can be seen as a material that stiffens the structure or serves as an isolation of the original structure from the lining, making it easier to reverse the treatment. All this implies that a lining can have many purposes, depending on each individual case and the choice of the conservator.

Some lining materials shrink in high relative humidity (many types of canvas made from natural fibers) or low relative humidity (collagen-based glues in particular and paper interleaves made from natural fibers), and some are relatively flexible, whereas others are stiff when tensioned. These properties usually vary depending on the direction of testing. Most lining materials are anisotropic, as is the case for woven canvases. All these characteristics can have an effect on the structural and mechanical properties of the lined painting as a whole. A very thin layer of collagen-based glue can have a much more significant effect on the forces developing in a painting structure than a much thicker layer of a minimally hygroscopic material.

The change that a lining represents must be well defined in order to know whether the original purpose of the intervention is being met and if there are possible side effects. Thus, this knowledge constitutes a basis for future decisions about conservation and the climate around the painting.

Numerous factors govern how paintings behave at different temperature and relative humidity levels. Therefore, in order to get a first impression of the impact that linings may have on paintings two approaches are possible. One is to test lined painting mock-ups in the lab and measure their response to relative humidity. The other is to look at lined paintings in collections. However, when looking at paintings, it is difficult to know which causes originate the different degradation phenomena. The following presents a brief review of what is known from lab tests.

Each layer in a painting has a different moisture coefficient of expansion and therefore responds differently to changes in RH. The resulting force in a restrained painting was shown to be governed by the principle of superposition (Mecklenburg, 1982). This principle states that when a composite material is subjected to an external load, caused, for example, by a change in RH or tensioning, the resultant forces are equal to the sum of the forces in the separate layers, provided that all of the materials are maintained at the same degree of restraint (Hearn, 1997). When adding the measured forces in the individual layers of a painting, it is possible in theory to predict the behavior of the lined painting. The total force (F) in a painting will be equal to the sum of in-plane forces in each material in the measured direction. For any given moisture, temperature, and strain level the following therefore applies:

$$F_{(\text{painting})} = F_{(\text{canvas})} + F_{(\text{size})} + F_{(\text{ground})} + F_{(\text{paint layer})}.$$

The assumption is that the force developed in each restrained material does not affect the force on the other materials. Therefore, it should be possible to test each material separately and calculate the combined effect on the painting. This principle was used by Mecklenburg (1982) to predict the response of a restrained painting and has also proven useful when lining materials are added (Andersen and Nielsen, 2012). For a lined painting the equation would look like

$$F_{(\text{lined painting})} = F_{(\text{painting})} + F_{(\text{adhesive})} + F_{(\text{lining canvas})}.$$

However, when the different layers interact, it becomes more difficult to predict what will happen. When a linen canvas is impregnated with an adhesive, as was often the case in older methods like glue-paste and wax-resin linings, the adhesive can interact with the swelling or shrinking canvas fibers and create an unexpected effect.

In a study of lining methods, the two traditional lining techniques, glue-paste and wax-resin, showed the biggest development in forces but in very different ways (Andersen, 2013). The wax-resin samples did not have a significant response at low relative humidity, but at levels of above 60% there was a slow but significant increase in force over 24 hours. The wax-resin mixture fills the voids between the swelling fibers in the threads of the lining canvas, and the original canvas seems to be the cause (Andersen et al., 2014). Compared to glue-paste, wax-resin is rather ductile and, contrary to what was expected, permeable to water molecules (Andersen et al., 2014). The absorption is slow, but the resulting forces in the painting structure can be remarkably high within 24 hours. This outcome indicates that understanding canvas geometry and canvas-adhesive interaction is vital to elucidate the problems with unwanted forces in lined paintings. It is evident that future research has to focus not only on moisture uptake but also on the resulting forces to obtain a fuller picture of the situation. In the results reported previously, the weft direction was much more prone to shrinkage after impregnation with wax resin than the weave direction, which indicates that the properties of the canvas still play an important role in the structure even if it is completely embedded in wax and resin (Andersen et al., 2014).

Animal glue has been the traditional glue to use in many crafts and for many purposes. In conservation it is known to be strong and stiff but also to be hygroscopic and change dimensions in both low and very high RH (>90%) with a risk of cracking (Karpowicz, 1990; Krzemień et al., 2016). It follows that traditional glue-paste lining techniques can cause the development of high forces in a painting structure (or contraction if the painting is not sufficiently tensioned; Tassinari, 1974; Young and Ackroyd, 2001; Andersen, 2013). Cracks in the corners of paintings have been regarded as an indicator of the high forces caused by contraction of, especially, animal glue, as this material imposes a risk of fracture in the paint layer as well as in the glue-paste layer itself. Cracks can also then act as expansion joints that will decrease the risk of further cracking by decreasing the forces developing in the structure. The glue-paste lining of a painting mock-up developed more force than a similar, but cracked, sample because the cracks were acting as expansion joints that released the forces (Andersen, 2013). Aged or cracked glue-paste films in linings may therefore be of less concern when it comes to forces developing in the structure.

Modern lining methods have introduced the use of minimally hygroscopic and stiff canvases for linings (Hedley, 1981; Mehra, 1981; Hedley and Villers, 1982), and they have been able to decrease the amount of response to relative humidity in the structure (Andersen, 2013) even though some have been found to be more responsive to humidity than expected (Young and Jardine, 2012). Furthermore, because of its high stiffness polyester sailcloth has been shown to maintain a higher level of tension after stretching the lined painting than the untreated painting or the same painting lined on a linen support.

Linen or cotton canvases are, however, still used for linings as they are thought to be more in line with the original structure. Using modern adhesives such as BEVA and acrylic emulsions on such flexible canvases was found to have three risks. First, in-plane movements are not prevented when the original canvas is not restrained by a stiff structure. Shear forces between canvas and paint layers will increase, and therefore, a higher risk of cracks and delamination of paint is possible. Second, the extra linen support will typically respond to very high RH or water damage by severe contraction that can cause more flaking and buckling than if the painting had been left unlined (Andersen, 2013). Last, when the painting is retensioned after lining, extra forces will be added directly to the paint and ground layers if the support is not stiff, and subsequent contraction forces due to changing RH will further add to the risk of paint loss. This is also the case when paintings are retensioned after strip lining.

A THREE-STEP APPROACH TO STRUCTURAL CONSERVATION

Damage in the form of tears, cracks, microfissures, delamination, etc., observed in paintings is the consequence of specific failure mechanisms. They represent a great complexity in day-to-day conservation practice since they are evidence of different failure mechanisms and therefore require special consideration. In such a scenario, understanding what the objective of the conservation actions are becomes crucial and requires a multistep approach, as suggested here (Figure 3).

First, the design of conservation treatments necessarily implies defining the needs, priorities, and limitations. To do so, it is crucial to determine what caused the damage, when failure took place, and the consequences for the painting materials. Conservators have traditionally been trained to identify and define the types of alterations observed in the painted surface and to provide solutions to technical and aesthetical problems. Studies of the chemistry and mechanics of paintings in recent decades have contributed to linking

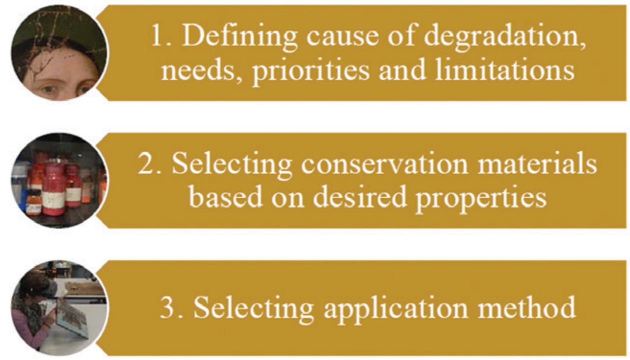

FIGURE 3. A three-step approach to developing a conservation approach.

scientific research to conservation practice. However, although chemistry has been incorporated progressively into conservation practice, understanding the exact physical mechanisms involved in degradation as well as the structural consequences of some conservation treatments needs further attention.

The second step is selecting conservation materials. The structural treatment of paintings is linked to the use of adhesives and sometimes also to the addition of new materials, such as fabrics, fillers, etc. The significant research developed in recent decades on adhesives can help conservators decide which adhesives (type of polymer, composition, molecular weight and size, glass transition temperature, adhesive/cohesive strength, etc.) to use in each case as well as which solvent and in what concentration. Nevertheless, in actual practice once the goals have been defined, many questions arise: How much strength, stiffness, and flexibility is really needed? How does the selected solvent influence such properties? What will the effects of such solvents be inside the painted layered structure in the medium to long term? How will the selected adhesive behave and age inside the painted structure, or what will the consequences of the irreversible impregnation of a porous painted structure be on mechanical and dimensional properties?

The third and last stage in the proposed multistep approach consists of determining how to actually carry out the treatment itself, that is, how to select the appropriate application method according to the needs (i.e., extent of penetration needed, quantity of adhesive needed, additional materials needed, etc.). The chosen method should preferably minimize interference with the painted structure (substrate porosity, existence of cracks or fissures to access the areas needed, side of the painting to treat, etc.) with consideration given to the possibilities and boundaries of the adhesive itself (wettability, viscosity, drying time, drying shrinkage, etc.). Although some work has been done in this direction (Maheux and McWilliams, 1995; Buzzegoli et al., 2008), it is sometimes difficult to know if the applied adhesive(s) penetrates into the location in the structure where it is needed.

DISCUSSION AND CONCLUSION

In 1969 the American conservator Sheldon Keck wrote that many treatments were not based on an understanding of the forces involved and that some of the treatments performed aggravated the stresses that they were attempting to overcome or created new ones (Keck, 1969). In 1984 the Canadian paintings conservator Barbara Keyser argued that this was still true (Keyser, 1984). From a current perspective, conservation methods have not evolved much since then, but interventions have become fewer, with an increased focus on avoiding overtreatment of paintings and preserving the original integrity.

When looking at the degradation consequences of conservation treatments from the past, it becomes evident that there is a need for better knowledge of the composition of both artists' and conservation materials. History points out the need for critical selection of stable materials and methods that fulfill structural needs without unwanted interference and allow future retreatability. Composition and structural compatibility deserve special attention as they can help explain the extent of damage that can be induced when altering the properties of paintings, including the potential changes in response to environmental fluctuations. For example, it is well known that the use of water-sensitive adhesives will enhance paintings' response to the environment and that cradles may increase forces in the original structure of a panel painting. However, the finding that wax-resin-lined paintings may develop much higher forces with prolonged exposure to RH levels above 60% than unlined painting is less known. As research slowly progresses, more precise conservation guidelines can be suggested to improve the stability and long-term preservation of structurally treated paintings.

This chapter has discussed the effect that conservation decisions have on the long-term preservation of paintings, and possible approaches to conservation and research into structural treatments were suggested. Furthermore, if the effect of past treatments is better understood, climate conditions can be tailored to meet the needs of specific objects that have been treated by conservators. For example, we have shown that some conservation treatments such as glue-paste linings have limited the window for nondamaging climate fluctuations. Impregnations with a minimally hygroscopic substance like wax resin that penetrates deep into the canvas structure, thought to prevent moisture response, instead increased moisture response at high RH (>60%). When layers are kept more or less discrete and adhesives are not impregnating the canvas, the principle of superposition can help predict if a lining or other layers will add to the forces developing in tensioned canvas paintings.

Further evaluation of the effects of conservation treatments will allow tailoring treatments to the specific relevant climates. This requires close collaboration between conservators and scientists in future research, not only to measure deformation in materials but also to measure or calculate forces because they are the direct course for cracks and deformation. A renewed focus on the consequences of structural treatments should help provide the much-needed assessment of relevant treatment options.

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