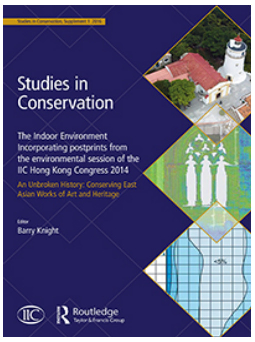

Studies in Conservation

ISSN: 0039-3630 (Print) 2047-0584 (Online) Journal homepage: http://www.tandfonline.com/loi/ysic20

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To cite this article: Terje Grøntoft, David Thickett, Paul Lankester, Stephen Hackney, Joyce H. Townsend, Kristin Ramsholt & Monica Garrido (2016) Assessment of indoor air quality and the risk of damage to cultural heritage objects using MEMORI® dosimetry, Studies in Conservation, 61:sup1, 70-82, DOI: 10.1080/00393630.2015.1131477

To link to this article: http://dx.doi.org/10.1080/00393630.2015.1131477

Published online: 12 Aug 2016.

Supplementary issue paper

Assessment of indoor air quality and the risk of damage to cultural heritage objects using MEMORI® dosimetry

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Air pollution is one of the environmental influences that degrade cultural heritage objects situated indoors. Other essential influences, such as temperature, relative humidity, and light are often well monitored. The presence of air pollutants is less often measured or included in risk assessment. The MEMORI® technology presented in this paper was developed as a tool for easy measurement and assessment of the general risk of degradation of heritage objects situated indoors due to indoor exposure to air pollutants. MEMORI dosimetry was performed in locations belonging to English Heritage and Tate (both located in London) and the National Archives of Norway in Oslo, to assess air quality. The related damage risk for collection objects and the protection offered by display and storage designs was assessed. A high level of acidic effect was observed inside a number of showcases, and a high level of oxidizing effect was observed in some room locations. Relatively simple mitigation measures, such as constructing tightly sealed showcases using low emitting materials, installing active carbon absorbing media inside a 'microclimate' frame, and using cardboard storage boxes for paper, significantly improved air quality. Overall, implementation of such measures is likely to improve the preservation of objects and reduce conservation costs.

Keywords: MEMORI® dosimeter, Microclimate frame, Showcase, Movable cultural heritage, Indoor air quality, Air pollution, Preventive conservation, Organic acids

Introduction

To safeguard movable cultural heritage objects, adequate preventive conservation measures need to be taken. These aim to minimize the environmental load and the consequent risks to the objects' integrity and preservation. The immediate environment around an object has contributions from the external environment and also from internally generated pollution. Objects interact physically, chemically, and with bio-agents in the atmosphere. For conservators, it is a complex task to understand how interaction can damage objects and how the damage can be avoided or reduced. Detailed assessment of an object's present and changing condition and observation of the local environment are needed. A material response table was developed as an initial aid that indicates material sensitivity to environmental factors (MEMORI-1, 2015). Environmental meters (e.g. temperature, humidity, pollution, light), as well as various kinds of dosimeters that mimic the impact of the environment, are common and necessary measurements tools (Rosenberg *et al.,* 2015).

The MEMORI® dosimeter technology (MEMORI-1, 2015) was developed in the EU project MEMORI (MEMORI-2, 2015) as a tool for conservators to assess air quality risk to objects located indoors. A website has been developed to provide information about damage risks in order to support decisions on mitigation methods (MEMORI-2, 2015).

This paper reports MEMORI dosimetry results and damage risk assessment for objects (MEMORI-1, 2015) in three institutions: English Heritage, Tate (both located in London), and The National Archives of Norway located in Oslo. The paper discusses how the location properties determine the air quality, and possible measures that could reduce damage risk to the collections by improving the air quality.

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Received March 2015; revised paper accepted September 2015
DOI 10.1080/00393630.2015.1131477

English Heritage conducted MEMORI measurements in rooms and showcases in Apsley House in central London and Ranger's House in Greenwich on the outskirts of London (Figs. 1 and 2). Tate carried out measurements inside a 'microclimate' frame in air-conditioned spaces at Tate Britain in central London. The National Archives of Norway conducted measurements in a storeroom and inside a storage box for documents within the storeroom. Their building is located in the northern perimeter of Oslo at the edge of the uninhabited forest. All the locations had conservation issues related to the amounts of air pollutants present, the risk for damage to objects, and possible needs for mitigation.

Conservation issues and measurement locations

The MEMORI measurements were performed to address certain conservation issues:

English Heritage

In Ranger's House, the dosimeter measurements were performed in three showcases in the bronzes room: a corner wall case, an alcove wall case, and a desktop case, and in the room itself. Ranger's House is situated at a distance of 500 m from a busy major road, in parkland. The room, which was monitored, is quite small, often closed, and contains wooden floorboards and furniture.

The two wall cases were expected to provide a good degree of protection against the ingress of the oxidizing pollutants in the room and any high relative humidity (RH) periods. All showcase materials were Oddy tested (Robinet & Thickett, 2005) before use, and therefore, it was expected that the internal materials should not emit significant amounts of organic acids. However, there was an internal source of organic acids: the baseboards were Medium-Density Fiberboard (MDF) and coated with Dacrylate 103-y, a material known to be permeable to organic acids (Thickett *et al*., 2006, 1998; Thickett, 1998). The desktop case has a much higher surface area-to-case volume ratio and is likely to have had a lower air exchange rate, generating a much higher organic acid concentration. The bronze objects in this case are being monitored visually and with portable colorimetry, Fourier Transform Infrared spectroscopy, and Raman spectroscopy to detect any early surface change on objects. Monitoring of RH and temperature has shown that the case does not exceed an RH of 75%, and only reaches that value for a few hours per year.

In Apsley House, the dosimeter measurements were performed in a showcase in the plate and china room, and in the room itself. Apsley House sits on an extremely busy road junction and is only 5 m from the traffic. The discontinuation of the western London emission control zone by the Mayor of London in 2009 resulted in a 40% increase in nitrogen dioxide concentrations in Apsley House. The showcase is wooden framed and dates from the 1840s. It is original to the Duke of Wellington's occupation of the house and its subsequent opening as a visitor attraction. The air exchange rate is 0.8/day. The showcase has unglazed biscuit porcelain objects.

Tate

A modern painting, The Francis Bacon triptych, N06171, *Three Studies for Figures at the Base of a Crucifixion*, 1944, which was constructed from poor-quality materials thought to be emitting organic acids, and painted in pigments that may be sensitive to them, was selected for measurement. Longer term studies on the condition of the paint are ongoing. This Francis Bacon triptych, which is usually displayed at Tate Britain, when it is not on loan, consists of three separate painted panels, framed individually in three frames (Hackney, 1999). Each original frame is enclosed using a standard procedure for paintings in the collection by adding wooden battens to deepen the frame at the reverse and then attaching (using screws) a sheet of oil-tempered hardboard to the verso to enclose the painting support. A sheet of Melinex (polyester film) is attached to the inner side of the hardboard. The front of the frame has a sheet of low-reflecting glass inserted into its rebate to complete the enclosure. There is a thin cushioned wooden slip (approximately 5 mm deep) to isolate the front of the painting from the glass, which is taped in place using a continuous tape of gum-coated Kraft paper. The backboard is sealed on the outside with the same tape. This design is to exclude dust and external gaseous pollution. It also maintains even moisture content, by providing buffering against temperature and relative humidity fluctuations, and prevents accidental damage to the vulnerable, unvarnished surface of the paint. By the creation of a rigid box structure in this way, the frame is often considerably strengthened, thereby providing further protection in transport and handling. These precautions should not be evident whilst on display (Hackney, 2007), and they are applied routinely at Tate to all framed paintings, unless it is considered inappropriate, or the painting is too large to glaze.

The 'microclimate' glazed museum display frame, described above, was developed when external air pollution was a serious problem and air-conditioning was relatively rare. Its origins are a report on the National Gallery (London) in the mid-nineteenth century (Eastlake *et al*., 1850). The principle remains sound and externally generated pollution is excluded. However, when the priority was to protect paintings from external pollution, insufficient attention was

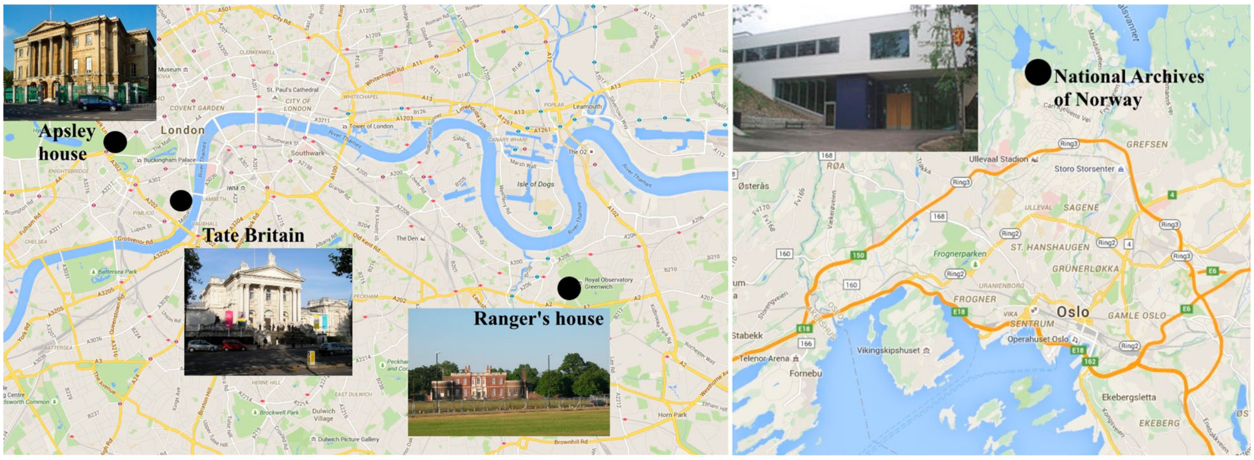

Figure 1 The measurement sites (photos: Google maps, Wikipedia).

given to the choice of materials being enclosed with, and around, artworks. The present concern is that internally generated pollution, which is not one of the major causes of deterioration in open storage, may be present in high concentrations in enclosed spaces and therefore should now be considered. Measurement of volatile organic acid concentrations is an important step in this study.

A MEMORI dosimeter was mounted inside one of the three Francis Bacon frames (Fig. 3) and removed after three months (6 January – 7 April 2014). The frame was then provided with a sheet of carbon cloth, of the same area as the (non-traditional) panel support and placed next to its reverse side, to act as a pollution adsorber, and a new MEMORI dosimeter inserted behind this for three months (7 April – 7 July 2014). In each case, the dosimeter was placed in the space between the back of the panel and the Melinex covered backboard, located so that air could circulate over both surfaces of the dosimeter. Except for the installation of the sorbant, the frame was in all other respects unchanged from the first MEMORI dosimeter exposure, and the same procedures for fitting the painting in the frame were used to provide a similar seal. From previous measurements of frame enclosures of this sort, the air exchange rate would have been approximately 1.9/day ($T_{1/2} = 9$ hours). The work was carried out in the filtered and air-conditioned conservation studio. The painting was immediately returned to display in a newly refurbished air-conditioned gallery for the three-months duration of each exposure. Externally generated air pollution was therefore effectively excluded from the frames.

The National Archives of Norway

The main objective with the measurements was to evaluate the amount of off-gassing from cardboard 'historical' storage boxes and the possible adverse effects on the stored parchment and paper archival records, belonging to the 'Special Collections' of the National Archives of Norway.

The boxes were specifically designed for the storage of these materials, but constructed with different types of high impurity, chemically unstable, low-grade

Figure 2 MEMORI measurement locations in English Heritage sites. (A) Apsley House, plate, and china room. (B) Ranger's House, bronzes room, showing the centre showcase (desktop) in foreground, the alcove case back left, and the corner case back right (photos: © English Heritage 2015).

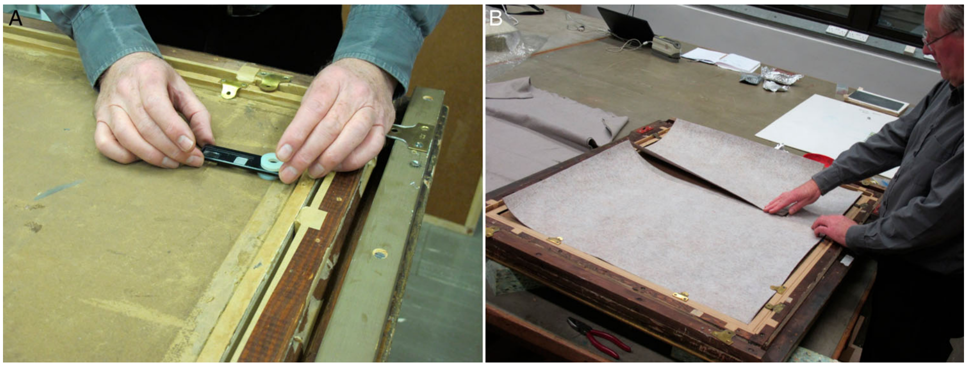

Figure 3 (A) Fixing the MEMORI dosimeter close to the verso of the panel inside the middle Bacon Frame (sitting face down on a table) using spacers on either side to ensure air circulation. The backboard was placed on top and attached to the frame edges. (B) Inserting carbon cloth over the verso of the panel in the Bacon frame before positioning the second dosimeter, as shown (photos: © Tate 2015).

boards. The oldest units were manufactured in the 1930s and progressively replaced in the early 1970s by newer models. The design evolved throughout the years, but the quality of the materials did not improve until the very latest ones fabricated in the late 1990s.

Over 10 000 parchment records from the eleventh to the sixteenth century and around 7000 historical paper documents dating mainly from the seventeenth and eighteenth centuries have been kept in these boxes for decades. Improvements, such as interleaving buffered papers to counteract acid migration, have been introduced over time, but there was a concern that internally generated pollutants could build up inside the boxes.

In this context, the measurements were performed to assess the levels of air pollutants within the boxes and evaluate their degradation effect on the different types of archival materials stored inside. The main reason for using the boxes is the protection they are expected to offer not only against gaseous air pollutants from outside the boxes, but also against other damaging external influences such as dust/particulates, light, and handling risk.

MEMORI dosimeters were mounted in a storage room and inside two high-lignin-content solid board boxes, one with and the other without documents, located in the storage room (Fig. 4). The storage room had mechanical ventilation with temperature and humidity regulation keeping an approximately constant relative humidity of 50% and a temperature of 20°C in the room. Particulate filters were mounted in the ventilation in-flow to the room. The ventilation rate for the room was approximately 24 air exchanges/day, with 90–95% air recirculated. For the closed boxes the air exchange rate was significantly lower.

The MEMORI technology

MEMORI is a system designed for measurement of indoor air quality and assessment of the risk of damage to sensitive cultural heritage objects. MEMORI was developed specifically for museums, archives, historical buildings, and other heritage institutions. The MEMORI technology was developed through work in several EU projects over more than 10 years and was finally presented after the EU project MEMORI. The Norwegian Institute for Air Research (NILU) co-operated with the Fraunhofer Institute in Germany in the development of the dosimeter and with English Heritage in the UK, in the development of the system to compare measurement results with the damage risk for cultural heritage objects. Eleven other European research and cultural heritage institutions and companies were partners in the MEMORI project (MEMORI-3, 2015).

The MEMORI technology consists of a dosimeter, a small dosimeter reader, and the MEMORI web pages for evaluation of results, and information on

Figure 4 MEMORI measurement locations in the National Archives of Norway. (A) store room, (B) archive solid board boxes, (C) measurement in box without documents, and (D) measurement in box with documents.

materials. The 'MEMORI dosimeter' has two small dosimeter samples, which react with the air, supported on a single holder (Fig. 5).

The MEMORI technology is used to assess the general risk of damage to objects from the effect of oxidizing and acidic air pollutants at the temperature, humidity, and light levels during its exposure. One dosimeter glass ('Early Warning Organic', EWO) is covered with a thin synthetic polymer film. This reacts with oxidizing gases in the air, such as nitrogen dioxide (NO_2) and ozone (O_3), and with UV light, at rates depending on the temperature. The other glass ('Glass slide dosimeter', GSD) has a special composition designed to resemble potassium-rich historical glass, prone to deterioration (Mottner, 2007). It reacts especially with acidic gasses, such as organic acids and sulphur dioxide (SO_2), dependent on the relative humidity (Dahlin, 2010). Sulphur dioxide has also been found to affect the EWO polymer at high relative humidity (> 70% RH) and high concentrations (> 60 ppb). The detection limits of the dosimeters are, for a three-months exposure period, approximately 4 $\mu g/m^3$ NO_2+ O_3 (EWO) and 10 $\mu g/m^3$ acetic + formic acid (GSD), but they are expected to depend on other environmental factors such as UV-light (EWO) and relative humidity (GSD). The reactivity of the EWO polymer and GSD glass indoors is well known. By measuring the changes in the polymer and glass after exposure, the general quality of the indoor air can be determined (Grøntoft *et al.,* 2010).

Other pollutant gases can also damage objects. The effect of reduced sulphur or chlorides on the dosimeter has not been examined. The concentrations of these pollutants are usually very low indoors, but they can still have a significant effect on some sensitive objects, for example silver.

The MEMORI dosimeter is mounted in a vertical position to minimize dust deposition. Particle deposition has not been reported to affect indoor-mounted dosimeter results. However, clearly visible particle deposition and higher readings for the dosimeter have been recorded at dusty outdoor locations. Any such 'other' pollutants that may damage objects, suspected of being present, should be assessed by different methods than MEMORI.

On insertion in the accompanying dosimeter reader, the MEMORI dosimeter is measured automatically (Fig. 6). An initial measurement is performed before mounting of the dosimeter in its chosen location and a final measurement is made after dismounting.

The change of the polymer and glass, due to exposure to the indoor environment, is measured as a reduction in the transmission of UV (EWO) and IR (GSD) radiation, at specific wavelengths. The measurement results are stored in the reader, to be subsequently uploaded to a PC and then to the MEMORI results web pages. Direct uploading from the reader instrument to the web pages is forthcoming. The MEMORI web pages are an integrated part of the MEMORI tool. Evaluation of the results is based on a three-months exposure period for the dosimeter. The relatively long exposure time makes the dosimeter very sensitive towards small concentrations of air pollutants and increases the likelihood that the result represents the average exposure for the objects. However, the dosimeter is less well suited for quick assessment of conditions before, e.g. loans or temporary exhibitions or during transport. When the exposure time is short, the sensitivity is less, but aggressive conditions over threshold levels can often be determined. As pollution exposure can vary significantly between seasons or years, it is recommended to make repeated exposures (Grøntoft *et al*., 2013).

The results are displayed on the web page as a 'traffic light signal'. The user can select between 22 heritage materials for the risk evaluation. 'Green' indicates that, within the constraints of present knowledge, it is unlikely that the materials will change significantly within a period of perhaps 30 years. 'Red' indicates

Figure 5 The MEMORI dosimeter.

Figure 6 Measuring of the MEMORI dosimeter.

that damage is likely to occur to objects within three years and that damage will require interventive conservation. 'Yellow' indicates a situation in between. The damage risk evaluation was made for a situation with a relative humidity of 50% and a temperature of 20°C. The dosimeter responds to varying relative humidity and temperature, like most materials, but the relative changes in damage risk due to changing relative humidity and temperature, as compared with the heritage materials, were not considered in the risk evaluation. Thus, the actual risk could be different at varying relative humidity and temperature and more caution is then needed in the interpretation. The temperature and RH should be measured throughout exposure to identify any extreme conditions.

The risk indication is also provided in a diagram with presentation of the measurement values for the dosimeter polymer (EWO) and glass (GSD) on the separate axis (Figs. 7–9). A comparison between the dosimeter response and the damage risk for the included materials was performed, based on research in the EU MEMORI project (MEMORI-1, 2015; MEMORI-3, 2015) and on information available in the conservation literature.

As the indoor air influences on the dosimeter response are known, the diagrammatic evaluation can be used for first instance diagnosis of an air quality problem. A high value on the horizontal 'EWO-axis' usually indicates little protection against nitrogen dioxide (NO_2) and ozone (O_3) coming from, for example, urban traffic. This is a typical result for naturally ventilated buildings in cities. A high value on the 'GSD-axis' usually indicates high amounts of organic acids, usually emitting from construction materials. This is a typical result in a showcase made with wood.

The MEMORI dosimeter measures the combined impact of the indoor environment on the sensitive dosimeter materials. It can be argued that such measurements offer a more straightforward damage risk assessment for heritage objects than measurements of single pollutant concentrations in air. The risk assessment is performed by comparing the environmental impact on the dosimeters, as described by dose–response functions (Grøntoft *et.al.*, 2010), with the expected impact of the environmental parameters on the different heritage materials. Owing to the complex interaction between indoor environments and different heritage materials, it is stressed that MEMORI measurements offers an indication of damage risk adding to the conservators' total understanding of the environment–object interaction.

The MEMORI web pages additionally give information about the sensitivity of many more materials used in cultural heritage objects toward specified air pollutants, how MEMORI dosimeter and material responses were compared, and how the air quality can be improved if a red or yellow MEMORI response is measured. After mitigation action, it is recommended that a second measurement be performed to check the expected improvement.

Measurement results

The MEMORI measurements in indoor locations of English Heritage, Tate, and the National Archives of Norway were performed during 2013 and 2014. The end dates for the three-months exposures are given in Figs. 7–9. The figures show the results as displayed in the diagrams on the 'Details' page on the MEMORI web pages. The materials selected for the evaluation were those judged to be most relevant for the respective collections. The damage risk to parchment, as was also found in the National Archives of Norway, is less than that to the lignin-free book paper in Fig. 9.

Table 1 shows EWO levels typical for European cultural heritage locations (Grøntoft *et al.*, 2010).

Discussion

The dosimeter reacts to the level of influencing pollution and climate parameters (see The *MEMORI technology* section). Properties of the locations, such as ventilation rates and showcase surface area to volume, will influence the values for the environmental parameters that impact on the dosimeter and the heritage objects. The main purpose of MEMORI measurements is to obtain a risk indication for the measurement specific location and relevant heritage object. A distinction made by MEMORI measurements, between acidic (usually from indoor), and UV light (UV is generally well controlled in heritage locations) and/or oxidizing (usually from outdoor) factors, serves this purpose. However, sources may be different depending on circumstances and, for detailed environmental diagnosis, measurement of single pollutant concentrations is usually needed.

English Heritage

Very different air quality conditions were detected by the MEMORI dosimetry in the six English Heritage locations. The six measurement results were clearly divided into three groups of two observations (Fig. 7):

1. Low results were obtained for two showcases, a corner case (a) and an alcove case (b), in the bronzes room in Ranger's House, Greenwich, London.
2. For two other showcases, a centre desktop case in the bronzes room in Ranger's House (c) and a showcase in the plate and china room in Apsley House (d), the result for the acid-sensitive GSD part of the dosimeter was high, whereas the result for the EWO detector, sensitive to UV light and oxidizing gases, was relatively low. The EWO measurement result

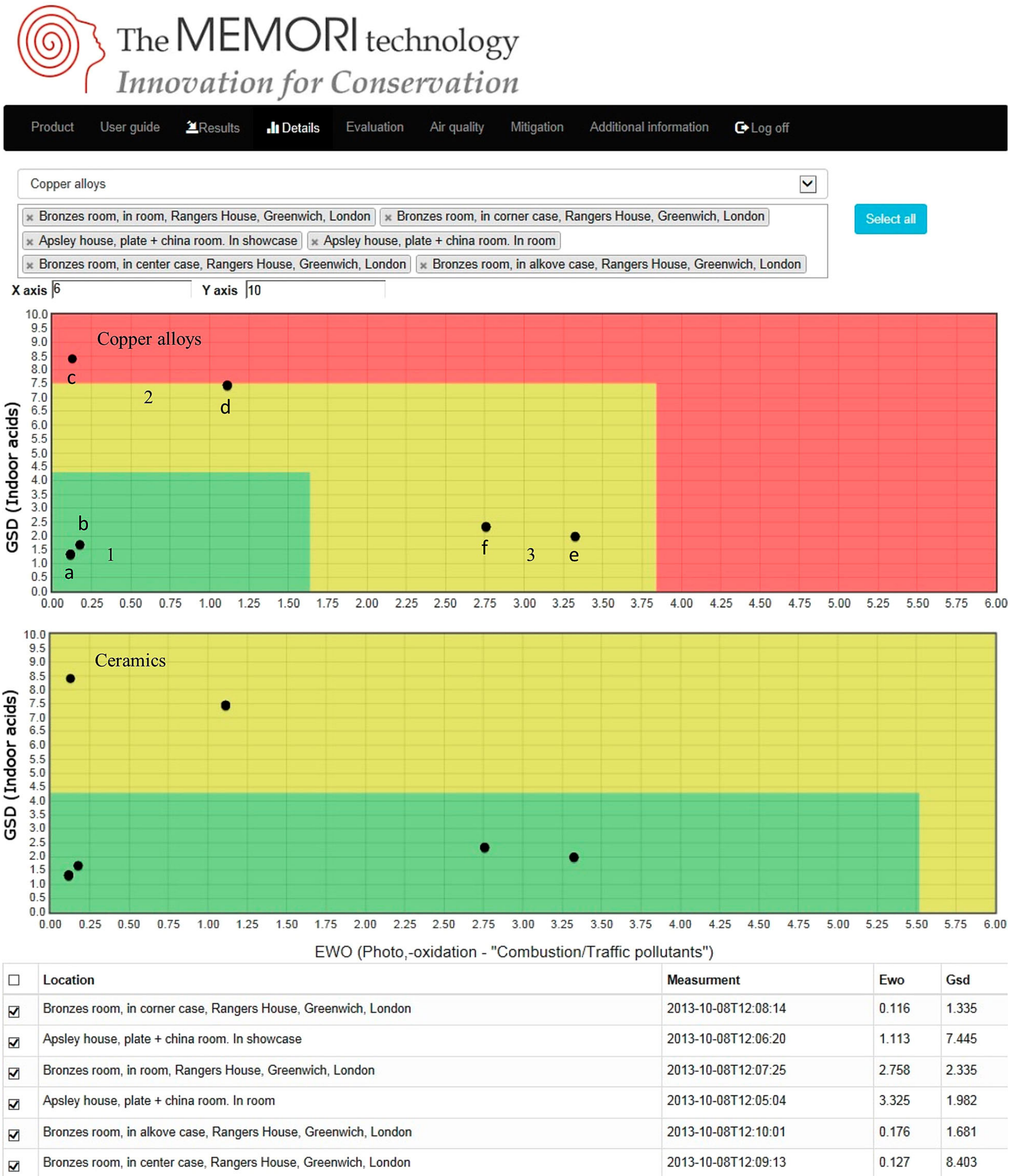

Figure 7 MEMORI results from measurements in English Heritage locations, with colour evaluation for copper alloys and ceramics. Three distinctive groups of two measurement results are noted on the upper diagram; the corner case (1a) and an alcove case (1b) in the bronzes room in Ranger's House; the centre desktop case in the bronzes room in Ranger's House (2c) and the showcase in the plate and china room in Apsley House (2d); and the plate and china room in Apsley House (3e) and the bronzes room in Ranger's House (3f).

was however substantially higher for the Apsley House case than for the Ranger's House case.

3. The two remaining locations, the plate and china room in Apsley House (e) and the bronzes room in Ranger's House (f), had relatively low values measured for the acid-sensitive GSD part of the dosimeter, but high values measured for the EWO part of the dosimeter.

The results for the corner and alcove case in Ranger's House (1a and b) indicate low levels of air pollutants, most likely due to low infiltration of outside room air into the cases and low rates of organic acidic emissions to the air inside the cases from the materials and objects in the cases. Despite the presence of an MDF internal source of acetic and some formic acid in the

Figure 8 MEMORI results from measurements in the Tate locations, with colour evaluation for sensitive pigments and varnishes; inside the Francis Bacon frame without carbon filter (g) and with carbon filter installed (h).

two showcases, the low surface area-to-case volume ratio appeared to result in low concentrations, and thus low GSD readings. It is unlikely that corrosion damage will be observed on copper alloys or ceramics in these cases within 30 years.

The results for the centre desktop case in the bronzes room in Ranger's House, and the showcase in the plate and china room in Apsley House (2c and d), indicate low levels of air pollutants infiltrating from the room air outside the cases, but high levels of organic acidic emissions from the materials in the cases. The high GSD response in the case in Ranger's House (2c) is probably due to its higher surface area-to-case volume ratio and likely lower air-exchange rate than the two other showcases in Ranger's House (1a and b). This results in greater accumulation and higher concentration of organic acids inside the case. The surface area-to-volume ratios for Dacrylate-coated MDF in the centre desktop case (2c), the alcove case (1b), and the corner case (1a) (Fig. 2) are 29.4, 10.1, and 4.6 m^2/m^3 respectively, which follow the order of the GSD results quite well. Despite the relatively high air exchange of the showcase in the plate and china room in Apsley House (2d), the large amount of wood present seems to generate a high acetic acid concentration and high GSD response.

A risk of surface corrosion is indicated within three years on copper alloys in the case in the bronzes room in Ranger's House (2c) and within 30 years on sensitive ceramics in the showcase in the plate and china room in Apsley House (2d) (Fig. 7). This could be due to high acidic concentrations and/or sufficiently

Figure 9 MEMORI results from measurements in the National Archives of Norway locations, with colour evaluation for historical rag paper and lignin-free book paper; the storage magazine (i), inside the cardboard storage box with documents (j); and without documents (k).

Table 1 EWO levels typical for general types of cultural locations in Europe

Location	EWO level
Archive store/store room/enclosure (e.g. showcase or 'microclimate' frame)	<0.6
Purpose-built museum gallery	0.6–2.1
Historic house museum	2.1–3.5
Open display in open indoor structure	3.5–6.0
Outside store with no control, sheltered from weather and sunlight	6.0–9.3
Outdoor	>9.3

high relative humidity. However, the measured RH values, of consistently less than 75% in the bronzes room in Ranger's House, are unlikely to cause corrosion of copper alloys if acetic acid concentrations are below 3000 μg/m^3, or if formic acid concentrations are below 2000 μg/m^3 (Cano & Bastidas, 2002; MEMORI-2, 2015). Investigations into this risk are ongoing, with monitoring of acetic and formic acid concentrations and of the copper corrosion rate (Prosek *et al.*, 2014). The unglazed biscuit porcelain in the showcase is known not to be affected by organic acid. The yellow risk category in the

MEMORI diagram (Fig. 7) is a general warning about risk, including more vulnerable ceramic materials, such as salt laden or lead glazed ceramics that are known to be sensitive toward organic acids. For the unglazed biscuit porcelain objects, the risk from dust ingress and surface soiling is much greater, and the low air exchange rate is beneficial even though the monitoring has detected high degradation of the glass sensor.

More external pollutants appeared to be infiltrating into the showcase in the plate and china room in Apsley House (2d), giving a higher measured EWO value than for the centre desktop case in the bronzes room in Ranger's House (2c). This is almost certainly due to the location of Apsley House at the traffic hub, resulting in higher infiltration of nitrogen oxides. For 2010, the annual average NO_2 concentrations at Apsley house and Ranger's House were reported to be 90–100 $\mu g/m^3$ and ~35 $\mu g/m^3$, respectively, compared with an annual mean objective set by the London health authorities of 35 $\mu g/m^3$ and a rural background level around London of ~20 $\mu g/m^3$, showing highly elevated values of traffic pollutants outdoor of the locations, especially at Apsley House (Environmental Research Group, King's College London, 2015).

The EWO results for the plate and china room in Apsley House and bronzes room in Ranger's House (3e and f) indicate infiltration of quite large quantities of urban pollutants, most likely nitrogen oxides from traffic. The EWO levels are quite high, but typical for historic house museums in Europe (Table 1). The EWO result value for the room in Apsley House (3e) is significantly higher than that for the room in Ranger's House (3f), which may again be explained by higher outdoor levels and higher ventilation of traffic pollutants into Apsley House than into Ranger's House. The relatively low GSD levels in these rooms is most likely explained by the higher volume-to-surface ratios, than for the showcases, and higher ventilation rates, which dilutes the acidic emissions from indoor surfaces. The slight response on the GSD in the bronzes room in Ranger's House (3f) is almost certainly from acetic acid emitted from the wooden floorboards and furniture in the quite small, often closed, room. The higher ventilation of the larger plate and china room in Apsley House (3e), than the bronzes room in Ranger's House (3f), is likely to give the slightly lower GSD response.

In the two rooms in Apsley House (3e) and Ranger's House (3f), a risk of copper alloy corrosion within 30 years is indicated; but, in this case, most likely due to infiltration of air pollutants from outdoors, such as nitrogen dioxide, ozone, and possibly sulphur dioxide (Sacchi & Muller, 2005; Watt *et al*., 2009; MEMORI-1, 2015). Previous extensive measurement over the past 10 years has clarified that although a risk is indicated, the pollution and copper corrosion rates are actually acceptable (Thickett *et al*., 2012). This is due to the relatively low RH experienced within the rooms. The measurements indicated that the impact of air pollutants was too low in the rooms to be likely to cause damage to sensitive ceramics within 30 years.

The measurements in Apsley and Ranger's House show the importance of using showcases to protect objects in polluted urban environments, and to keep these showcases well sealed to prevent most of the infiltration from the rooms (Fig. 7, group 1). This is particularly important in historical buildings, which offer only modest protection against outdoor air pollution.

For sealed cases, it is a risk that large amounts of organic acidic pollutants, especially acetic and formic acid, are emitted from showcase and object materials, and are trapped inside the cases to accumulate to high concentrations (Fig. 7, group 2). The acids can damage objects and it is important to reduce their presence. The best mitigation actions is to build cases from low emitting materials, although care is needed to avoid later introduction of unsuitable materials such as MDF. Reducing RH, blocking pollution emission by barrier films, or absorbing air pollutants by installation of active carbon media can also be used (MEMORI-1, 2015). For the corner and alcove cases in the bronzes room in Ranger's House (Fig. 7, group 1), the general goal of a low air pollution and safe environment has been obtained.

Tate

The result of the first MEMORI dosimeter exposure in the unaltered frame (g) indicates, as expected, that levels of oxidizing pollutants in the enclosed space are very low and that the frame is performing its original design task of excluding them. However, the level of internally generated acidic pollutants is relatively high, confirming concerns about the materials within the enclosure. A paintings frame has an intrinsically high surface-to-volume ratio and low air exchange rate. The second MEMORI dosimeter exposure 'with carbon filter' (h) indicates that the carbon cloth is very effective, entirely eliminating the external oxidizing pollutants in this case, and reducing internally generated acidic pollution significantly.

The risk diagrams (Fig. 8) indicate that there is a risk of change to sensitive pigments within a 30-year period, even at very low doses of pollutants, and that installation of carbon cloth adsorbers will reduce but not entirely remove this risk. Lead-containing pigments and malachite have been found to be sensitive to acetic acid (Dahlin *et al*., 2013; De Laet *et al*., 2013). Lead white (basic lead carbonate) is present in most paintings of this date, although malachite is rare. For most paintings, the medium (oil) will provide some protection against gaseous pollution, but the Francis Bacon painting has very lean or underbound paint, meaning that there is little medium, which is a concern since the pigment is exposed to off-gassing from the support. Dried oil medium itself can cause off-gassing of free fatty acids, which can react with lead white pigment, so, in general, it is difficult to know which source poses the greater risk to the pigment, the support, or the oil. For the Bacon, the poor-quality support is suspected of being the highest risk. An important reason for glazing this painting in a microclimate-type frame is to protect the absorbent surface of the paint, and the exposed and un-primed support, from particulates. Although this painting is unvarnished and cannot be varnished, in general, by installing active carbon absorbing media, as identified in the diagram, the risk of significant change to varnishes, or any natural resins used by an artist, would likely be reduced to more than 30 years into the future (from yellow to green).

From what is known about the susceptibility of materials used in the painting, the present frame design could be improved in order to reduce volatile organic acid concentrations generated by framing materials. In the case of the Bacon triptych, however, the painting support itself is suspected of being a major source of pollution, since it is of a poor quality, degraded, and structurally weakened commercial board made from compressed wood fibres. The active carbon cloth reduces air pollution inside the 'microclimate' frame very effectively, but it is not known whether it prevents some organic acids emitted from the painting board reaching the paint film directly, potentially affecting certain pigments. This will depend on the rate of diffusion, reaction rate, and residence time of the acid vapours. These pollutants could be acting directly on the work of art without being present and measurable in the air adjacent to the carbon cloth. Removing acid vapour from the air by using a sorbant, such as carbon cloth, and thereby setting up a new more favourable equilibrium with acid trapped in the support will mitigate the problem, but some interventive treatment of the support, if practicable and safe for the artwork, might also be necessary to eliminate it completely.

The result is important in any debate on the remedial treatment of existing frames, since it shows that the use of sorbants can provide much improved conditions inside a 'microclimate' frame. A longer term aim of the present study at Tate is to measure the effectiveness of the carbon cloth at intervals over the next few years in order to estimate its useful lifetime. It is evident from work carried out during the EU MEMORI project that finding suitable inexpensive non-polluting structural materials to replace wood products and adhesives is not straightforward, but the MEMORI dosimeter could be used in the future to test new designs of frame enclosures.

The National Archives of Norway

The initial assumption was that an adverse environment existed inside the storage boxes; however, the data from the dosimeter measurements showed that the boxes themselves were not significantly emissive. The measurement values were low, representing, for the EWO part, a typical archive situation (Fig. 9, Table 1), which indicates that the boxes do not emit acids to give significantly higher concentration levels than in the room, or possibly that the relative humidity is lower in the boxes than in the room. In any case, the damage risk from acidic air pollutants to paper or parchment is likely to be slight and at a similar level in the room and inside the box. It is unknown how much the rate of emissions may have diminished throughout the years, but it seems that today the boxes are not endangering the parchment and paper records, but are providing a protective microenvironment against air pollutants in the storage magazine.

In a time of budget constraints, addressing the most important priorities is crucial for efficient management of finite resources. The dosimeter measurements have contributed to a decision-making framework for establishing priorities within a preservation programme, based, not on presumptions, but on the likely risks that these storage boxes pose to the archival records kept inside them.

Conclusion

MEMORI dosimetry was performed in locations belonging to English Heritage, Tate, and the National Archives of Norway to assess the air quality, the related damage risk for collection objects, and the protection effect offered by the location designs, including particular preventive conservation measures to improve the air quality. High levels of acidic impact were observed inside a number of showcases, and high levels of oxidizing effect were observed in some room locations.

Protective enclosures used by English Heritage and the Norwegian National Archives were found to significantly reduce the impact of oxidizing 'traffic pollutants', but potentially increase the impact of internally emitted organic acids. The observed pollution levels indicated a risk for observable degradation of bronze in less than three years in one showcase, and of bronze, ceramics, sensitive pigment, varnish, and historic rag paper, in less than 30 years in other locations. By the use of low emitting materials in English Heritage showcases, and installation of activated carbon cloth in a Tate 'microclimate' frame, the measurements indicated reduction of this risk to a situation with 'no likely significant change within a period of 30 years'. The use of the protective enclosures and relatively simple mitigation measures significantly improved air quality and reduced damage risk to objects, and thus increased the expected time between conservation interventions.

Environmental measurements, such as with MEMORI, and detailed understanding of the environment–object interaction, are needed to understand damage risk. For some of the English Heritage locations, it was found that the damage risk was less than indicated by the measurements. The unglazed biscuit porcelain objects on display are expected to be less sensitive as compared with the average of this object category for which the assumption was made in the database, and, especially, the risk due to variations in RH conditions should be considered besides the MEMORI assessment. For the case at Tate, a concern remained that contact between a painting and acidic support materials can still represent a damage risk when a low air concentration of the organic acids has been achieved.

Better understanding of the risks to individual objects can be obtained by more detailed description of the object materials and of their relative sensitivity to, and the sources of, different environmental influences. Detailed measurements of temperature, relative humidity, and light are usually needed and often undertaken. More detailed measurements of the levels of single pollution species may be needed. This shows again the importance of considering the wider picture that surrounds pollution. More detailed information is available about this on the MEMORI product web pages (MEMORI-2, 2015).

Our evaluation is that MEMORI dosimetry worked well and was a useful supporting tool to assess general air quality risk for damage to movable cultural heritage objects and effects of mitigation measures to reduce air quality risks.

Acknowledgements

This work was supported by the EU project MEMORI (Grant Agreement No. 265132) and the Norwegian Research Council project, MEMORI INC. For the establishment of the used risk diagrams, we would like especially to thank the MEMORI partners; BOKU-University of Natural Resources and Life Sciences, Austria (Paper materials); Royal Danish Academy of Fine Arts, School of Architecture, Design and Conservation (Parchment), University of Ghent, Belgium (Pigment), and University of Pisa, Italy, and Birkbeck College, University of London, Birkbeck, UK (Varnish) and Håvard Vika Røen at NILU who made the web design and did necessary updating.

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