Revisiting Reflectance Transformation Imaging (RTI): A Tool for Monitoring and Evaluating Conservation Treatments

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Abstract. Reflectance Transformation Imaging (RTI) has already been used for about twenty years in the field of Conservation and Restoration of Cultural Heritage for non-invasive condition assessment and documentation. However, its potential can be expanded. This paper will discuss the benefits of applying this readily available and low-tech technique to evaluate and monitor conservation treatments. Since the RTI software calculates the exact angle of the light for each RTI image taken, lighting conditions can be reproduced, leading to a standardisation of oblique light imaging. As a result, images produced before and after a conservation treatment can be compared. This allows for an objective evaluation of the treatment carried out and enables monitoring the condition of the painting over time.

1. Introduction
Reflectance Transformation Imaging (RTI) is a technique that is increasingly being used in the field of conservation. It is a computational photographic method that creates an interactive image, which highlights the object’s topography (the object’s surface shape and texture). It was first developed at Hewlett Packard Laboratories in 2001 and the open-access software has been further developed by Cultural Heritage Imaging (CHI) for its use for cultural heritage objects [1].

The technique has found applications for a broad range of objects for non-invasive investigation, condition assessment and documentation of both two- and three-dimensional objects [2]. Studies have included illuminated manuscripts, archaeological objects, ancient sea scrolls and coins. It has been used to give insight into minor surface details, typically not visible to the naked eye. It also aids in the identification of tool marks, materials and layer build-up, manufacture techniques and in stylistic comparison of objects. In several studies, RTI has proven to be a useful tool in the examination of panels and canvas paintings as it emphasises the three-dimensionality of the paint layer. These case studies also demonstrated the suitability of RTI in capturing gilded and tempera painted surfaces of icons [3, 4]. The majority of these studies to date have been diagnostic in nature.
The application of this readily available technique can extend beyond the diagnostic. This paper will present two case studies in which the authors intend to show the possibilities of using RTI as a tool for evaluating and monitoring conservation treatments, at specific moments during the conservation process and in the long-term. In this context, evaluation refers to the assessment and validation of results during and immediately after a treatment. The monitoring of a restoration treatment entails checking whether the structural stability of the object changes over time after a treatment is carried out. The case studies described will focus on the conservation of painted panels treated at Stichting Restauratie Atelier Limburg (SRAL). The applicability and effectiveness of RTI will be discussed in relation to its use to aid conservators within the conservation process.

2. How RTI works

Traditionally, to obtain information about surface textures - such as impasto, cracks, raised paint, damages, canvas weave and wood grain - raking light photography is used. This technique uses a low angle light source almost parallel to the surface. The light source emphasises the surface topography by creating shadows of the highpoints. Images captured are typically converted into black-and-white as any colour registration is distorted. More advanced raking light investigations may involve moving the light source to different sides of the object, adjusting the angle of the raking light to provide the most visibly effective result. This system is, however, limiting because each image taken is of a static moment and of a single angle. Additionally, shadows cast over the surface may mask adjacent raised details. RTI provides many advantages compared to this technique.

RTI is “a computational photographic method that captures a subject’s surface shape and colour and enables the interactive re-lighting of the subject from any direction” [1]. As the CHI website mentions, “the enhancement functions of RTI reveal surface information that is not disclosed under direct empirical examination of the physical object” [1]. RTI has a distinct advantage over traditional observations made using raking light. A single and unregistered angle of light is replaced by taking multiple high-resolution digital photographs of the surface of an object lit from different angles. The light creates different highlights and shadows for each individual image at each specific defined angle. The images are mathematically synthesised by free software, available from CHI. The RTIBuilder software is able to calculate the surface normal for each pixel of the image, in order to reconstruct the surface topography of the object. Synthesised light angles are created for the ‘gaps’ in the image. The captured images are stacked and registered so that they are overlaid exactly on top of one another. These images are merged into one virtual reconstruction of the surface and can be viewed in RTIViewer, a specific, separate programme. The images captured are in colour but can also be viewed in black-and-white. This system, thus, provides a photo documentation in visible light of the current condition of the object.

2.1.1. Light and set-up

The best images are taken in a darkened room and the light source needs to be direct rather than diffuse. The light source can be either a flashlight or a continuous light source. Different light angles can be achieved by constructing a dome, with numerous fixed positions for the lights, that is placed over the object. Alternatively, an upright stand that is moved around the object can be used with a light positioned at different heights. The dome system requires multiple fixed light sources on a rigid structure, whereas the second system can be constructed using a simple vertical stand and a single light source [6]. Both the dome and stand lighting rigs are more easily used with the object placed on the floor. The object can also be mounted on a vertical support, such as an easel when using the second system.

The background on which the object is placed for photography needs consideration. It should not contrast against the image, and thus it needs to be non-reflective and of a neutral colour. For the best result, a photographic backdrop can be used.

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1 Terminology of conservation and restoration treatments can be found on the ICOM-CC website [5].
2 Raking light is a term used in conservation and is commonly known as oblique light.
3 Surface normal: ‘the vector at right angles to the surface at that particular point’ [7].
2.1.2. Registration

The light angle for each image can be registered using a small, reflecting sphere. With this sphere as a reference point, the surface normals are calculated. The sphere should have a reflective, glossy surface and is preferably black. Literature mentions the use of different sizes, from very small ball-bearings to snooker balls. The size of the sphere depends on the size of the object and the distance of the camera to the object as it has to be well visible in each image. The cast shadow of the sphere should not cover the object. The sphere must not be moved during the capture of images within one RTI session. The reflection in the sphere is recorded and thereby the angle of the light can be registered. Since the sphere is static, the RTIBuilder software uses its position to stack and overlay the images captured.

A photographic colour checker is also included in the image capture to ensure adjusted colour registration for each image. This allows for an accurate colour adjustment in the capture and post-processing of the digital image.

2.1.3. Camera and software

The camera has to be placed in a fixed position, usually mounted on a tripod or a stand, that does not move from one image capture to another. Typically, a digital single-lens reflex (D-SLR) camera with high resolution capacity is employed. The higher the resolution of the camera, the better the final results will be. For best results, the camera can be tethered to a computer and controlled by a software programme such as Adobe® Lightroom [8]. This ensures that the camera is static while the image capture occurs, aiding the image processing during the next step. The image capture software allows the white balance to be set to the lighting conditions, providing a colour corrected image. Full colour information is therefore also obtained with each shot. Captured images are manipulated to remove extraneous information and ensure image consistency using a software programme such as Adobe® Photoshop. These images are further processed in the RTIBuilder software.

A minimum of 24, but better between 40-60 images, should be taken to obtain a good quality RTI image. The more images used, the less normals need to be constructed by the RTIBuilder software to fill the ‘gaps’ between the images taken. The captured images are then registered and stacked using the RTIBuilder programme creating an interactive, digital display of the object, which includes a movable light source. The processed image is viewed via the RTIViewer programme (fig. 1).

![Fig. 1. Digital display of the RTIViewer showing one of the case studies in the rendering mode ‘Specular Enhancement’ (Image: SRAL).](image)
The user can view the effect of different lighting positions on the surface of the object by moving the curser around the dynamic green mouse-pad, found on the right of the viewer screen. Full colour and raking light conditions can be viewed. Further digital processing manipulations of the image can be carried out. Features, such as ‘diffuse gain’ and ‘specular enhancement’, can be used to further highlight textural information.\textsuperscript{IV}

3. Methodology
RTI captures have become more regularly used at SRAL in the last few years. The technique is used to aid the conservator determining the condition of the object, such as the extent of flaking paint or deformations of the support, and to evaluate and monitor the results of conservation treatments. Two case studies will be described below. Both used a standardised system for taking the RTI captures (fig. 2).

The set-up for the RTI images taken at SRAL is as follows:
- The entire process is carried out in a dark room to eliminate light reflections other than those from the light source. Large objects are placed on the floor, which has a neutral grey linoleum covering. The smaller objects are placed on a green cutting mat, also placed on the floor. The grid pattern on the cutting mat aids the cropping of the image in the post-processing phase.
- The camera is mounted on a photographic stand with an extendable arm or attached to the ceiling. For larger objects, partial RTI images can be taken.
- The camera used is a NIKON D7100 with a zoom lens (AF-S NIKKOR 18-70mm, 1:3.5-4.5G ED). Image capture is set at the highest resolution in RAW format. Forty-eight images are taken, which is a number determined by the set light positions.
- An LED light source producing a direct beam is used. The LED lights were designed for SRAL by Van Kan and Willems, and consist of a 6x6 array set to daylight colour temperature via computer software.
- The position of the painting within the centre of the circle is recorded.

\textsuperscript{IV} Definitions of these features can be found in the glossary on the Cultural Heritage Imaging website [1].
The positions for the light direction are determined by first creating a circle around the object and marking twelve clockwise divisions. At each of the clock positions, four height angles are calculated using an upright stand on which they are marked. The light is positioned at each determined height for each position on the clock, which ensures consistency. Thus, 48 images are captured. The light angles can be reproduced by using the same lighting positions for future RTI captures.

- The reflective sphere consists of a small copper spherical ball painted black. The diameter of the sphere measures 2 cm and is placed adjacent to the object on washers to ensure they remain fixed in place during RTI image capture. Care is taken not to allow the cast shadow to cover the object.
- A colour checker (Qcard 203 Camera Color Calibration) is placed in view frame of the camera [9].
- The camera is tethered to the computer using Adobe® Lightroom. This allows remote viewing of the image, which is especially important when the camera is mounted at ceiling height. The software allows for image manipulation prior to image capture, as aperture, exposure time, and white balance can be pre-set and standardised. Following instructions in the RTIBuilder manual, the images are processed and stacked. This programme also calculates the normal angles, which are used to synthesise the final RTI file. The RTI file is displayed in the RTIViewer programme, which allows an interactive viewing experience of the reflectance transformation images.

The most expensive element of the RTI tools described above is the camera. Other materials used in the system are relatively inexpensive and can be purchased easily. The Adobe® software package is also relatively inexpensive. This makes the system readily available to a wide audience. The set-up of the photographic studio for RTI captures takes time, but does not need specialised expertise. Instructional manuals and videos are available not only from CHI, but also from various other sources such as Cultural Heritage Science Open Source (CHSOS) [1, 10 and 11].

4. Case studies
The following section will evaluate the RTI process as described by using two case studies. The first case study used RTI captures to compare and evaluate the development of the aesthetic treatment of a fifteenth-century panel painting. The second case study used before and after treatment RTI captures to assess the structural treatment of a sixteenth-century panel painting. The after treatment RTI capture will be used to monitor future changes in the structure of the panel that may occur under the influence of uncontrolled environmental conditions.

4.1.1. Case study 1: Spanish panel
The first case study concerns a Spanish panel painting by an unknown artist, dated between 1450 and 1475 (fig. 3). It belongs to the Suermondt-Ludwig Museum in Aachen. The artwork has gilded areas and is painted with both tempera and oil-resinous paint [12]. The five-hundred-year-old painting has had a long history of damages and related treatments. Recently, old varnish layers, repaints and fillings were removed. Losses in some areas extended as deep as the ground layer and required filling to bring the surface to a uniform level. It was important that the fillings would be well integrated into the original paint surface and that they would not be visible under museum lighting conditions. In this case, the RTI captures were used as a means to evaluate the quality of the applied fillings (fig. 4). The possibility of changing the light direction in the RTIViewer programme enabled the assessment of the height and texture of the fillings from all directions. Any fills that appeared disturbing in the RTI images were further adapted by the conservator to ensure their integration into the surface (fig. 5 and 6). In this way, a better result could be achieved.

The before and after RTI captures provide the conservator with two specific data sets that can be directly compared and assessed. In this case, the highlights present in the before treatment RTI

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V. The filling treatment was carried out by Cerys Fry, Fellow at SRAL (2017-2018).
capture are more pronounced than the RTI capture after the filling treatment. The reduction of the number of highlights shows that an improvement was made by the treatment. This allows the conservator to evaluate the treatment and improve the fillings further prior to integrating the fills to create a unified comprehensive image.

Fig. 3 and 4. Unknown master, *The Beheading of St. John the Baptist and the Feast of Herod* (GK84b). Circa 1475 Mixed media on panel, ~92 x 48 cm, Suermond-Ludwig-Museum, Aachen. Left image is a direct light photo before treatment. The right image is an RTI capture before filling treatment (Photos: SRAL).

Fig. 5 and 6. Left image shows the RTI capture before treatment and the right image shows the RTI capture after the application of fillings. Both images were taken with the exact same light angle coordinates. (Photos: SRAL).
4.1.2. Case study 2: The Dream of Jacob

The second case study involved a sixteenth-century, Southern-Netherlandish panel painting, entitled The Dream of Jacob by an anonymous artist (fig. 7) [13]. The painting belongs to the Basilica of Our Lady (Onze-Lieve-Vrouwebasiliek) in Maastricht. It required a structural treatment of the support as the original butt joints between the three wooden boards of the support had failed over time, and splits had occurred in the upper and lower boards. Further damage was induced by the application of a secondary cradle support. VI This had restricted the natural movements of the wooden panel in response to changes in environmental relative humidity. Tension build-up in the wood caused deformations in each individual board of the support to develop. In the field of paintings conservation such deformations are generally described as ‘wash boarding’.

The challenge of this treatment was to re-align the individual boards and create a levelled paint surface with a continuous curvature. VII RTI captures were carried out before and after rejoining the panel in order to assess the result of the treatment. Comparison of the RTI captures showed that the wash-boarding effect had strongly diminished after rejoining the boards (fig. 8, 9, 10 and 11).

In the future, the after treatment RTI capture can be used as a reference to assess if the support develops new deformations. The wooden support will continue to react to fluctuations in relative humidity as it is a hydroscopic organic material. Monitoring the degree of curvature of the panel over time will allow conservators to determine if compression tension builds up in the support. This can happen if the movement of the support is restricted as relative humidity varies. To monitor alterations in the condition of the panel, new RTI captures can be taken and compared with the existing after treatment RTI image. In this way, damage caused by factors such as adverse environmental conditions can be demonstrated and perhaps even prevented.

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VI A cradle consists of attached wooden members adhered to the reverse of the support in the same direction as the wood-grain of the support boards. Perpendicular sliding battens are inserted into half-lap inserts into the fixed members. The intention is that these flex as the panel support responds to fluctuations in relative humidity. The sliding battens often become blocked as the wood swells when absorbing moisture from the environment, negating their intended function. The aim of the cradle is to support the painting and maintain its flatness.

VII The treatment of The Dream of Jacob was carried out by Lauren ten Wolde, Fellow at SRAL (2017-2018).
Fig. 8 and 9. The top image shows the RTI capture before treatment and the bottom image shows the RTI capture after structural treatment. Both images were taken with the exact same light angle coordinates. (Photos: SRAL).
Fig. 10 and 11. The top detail shows the RTI capture before treatment and the bottom detail shows the RTI capture after treatment. Both images were taken with the exact same light angle coordinates. In the top image the light source emphasises the deformation of the lowest board, whereas in the bottom image the light source illustrates the continuation of the curvature. (Photos: SRAL).
5. Discussion
The first main advantage of using RTI as a tool for evaluating conservation treatments is the flexibility of this technique. In contrast to raking light photography - in which only one light angle is captured - RTI captures allow the light angle to be changed in a virtual reality. The light angle can be adjusted at each specific area, to obtain the most information about the surface texture of the painting. This is especially useful for strongly deformed wooden supports. In these cases, a single raking light photograph will not contain information about the whole surface of the panel as the shadow cast will extend over adjacent deformations, masking their severity. This problem does not occur when RTI captures are made.

A second advantage of RTI is the reproducibility of the imaging technique. If a consistency is kept in the lighting situation, it is possible to use the same set of lighting coordinates in the RTIViewer in the two captures. This allows for an accurate and reliable comparison between the different captures at different points in time. Differences visible between the captures can therefore be ascribed to actual differences in the surface shape and texture of the painting and not to a difference in the angle of the light. For example, the improvement to the curvature of The Dream of Jacob is substantial and is demonstrated by comparing the two RTI captures.

RTI also has drawbacks since the captures may be difficult to read. This was the case when interpreting the RTI capture of the Spanish panel. Here the surface is extremely irregular and comparing the overview RTI images taken before and after treatment did not show a distinct change or improvement. Zoomed images could be studied to provide more local information and allow for more detailed observations. These subtle details may be more easily determined by the eye of the trained conservator than that of a lay audience.

Although it is possible to create high-tech RTI captures using advanced equipment, the authors experienced that good quality RTI captures can be produced with low-tech tools. It requires time to arrange the whole set-up, however, once the preparation is done, making the actual captures can be done quickly. Therefore, it is possible to implement RTI in typical conservation studio practice.

6. Conclusion
RTI can be used beyond diagnostic application, as shown by the two case studies in this paper. The imaging technique proved to be a useful tool to evaluate the specific goals of the described treatments. Furthermore, the images that were obtained with RTI are valuable for documentation and as a tool for communication with owners and other stakeholders.

The flexibility of the RTI technique proved to be useful when evaluating highly irregular surfaces because the light can be placed at the best angle for each specific area in the virtual viewer programme. Moreover, because of the reproducibility of the RTI set-up, the exact same area can be viewed with the same light angle in a next RTI capture. This enables accurate comparison between the different stages within a conservation treatment, creating a valuable record for monitoring, evaluation, documentation and communication. The authors recommend that a more extensive use of this low-tech, easily affordable system could be wider implemented in the field of conservation and restoration.

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