

RTI and virtualRTI: tools and methodologies for documenting prehistoric engraved artifacts.

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Abstract – This study aims to contribute to developing a multidisciplinary methodological framework and a functional workflow tailored to the specific requirements of archaeological documentation and the investigation of prehistoric art.

Reflectance Transformation Imaging (RTI) was tested on engraved pebbles recovered during the archaeological excavations at Grotta di Santa Maria di Agnano (Ostuni, BR – Italy). The results indicate that the interactive processing of false-3D imagery significantly enhances the recording of fine details, thereby enabling the preliminary stages of a palaeographic analysis concerning the execution and stratigraphy of sign palimpsests.

The RTI-Highlights method emerges as a competitive and high-performing analytical approach, which can be implemented using low-cost equipment and a relatively straightforward operational workflow. Moreover, the continued development and widespread availability of open-source tools facilitate large-scale documentation of archaeological artefacts, promote future research, and ensure the long-term digital preservation of cultural records.

I. INTRODUCTION

The recurring challenges in the visualization, documentation, and analysis of graphic elements within the corpus of prehistoric artistic expressions constitute a significant obstacle to the interpretation of the complex grapheme-symbolic language system shared by Paleolithic hunter-gatherer societies [1, 2]. The difficulty in reproducing the intricate syntax of signs has had considerable repercussions on analyzing these representations. In many cases, pursuing greater legibility has led to deviations from an objective "transcription" of the signs in favour of a more subjective interpretation of thematic content [3, 4]. While identifying iconographic models in naturalistic-figurative expressions has not substantially altered the overall interpretation of their content, methodological rigour and the inaccessibility of specific sites and artefacts have hindered a

comprehensive understanding of the non-figurative and geometric-linear repertoire. The methods adopted by the pioneers of the late 19th century, aimed at producing precise and faithful graphic reproductions of prehistoric artworks, had already raised concerns – by the early 20th century – regarding the conservation issues associated with invasive techniques such as paper moulding and frottage (figure 1)[5]. Even the most effective tracings on translucent paper by Abbé H. Breuil, though innovative and more preservation-conscious, were ultimately deemed inadequate with the beginning of photographic documentation [6, 7].



Fig. 1. Direct recording of a parietal engraving and pastel reproduction of bovids at the Cave of Altamira by Henri Breuil [7].

The need to provide data suitable for the diagnostic analysis of Paleo-Mesolithic visual culture has thus led to the development of new forms of observation and interaction through digital technologies [9]. Consequently, the comprehensive and semiotic interpretation of prehistoric signs has shifted towards an interactive investigation of artefacts that focuses not only on iconographic analysis but on a broader examination of the phenomenon as a whole [10, 11]. The support of current methodologies and digital applications has enabled the emergence of increasingly non-invasive approaches that account for the contextual reading of the plastic values assumed by individual signs in relation to their physical support, the tools used in their creation, and the gestures involved [12, 13, 14, 15].

II. ARCHAEOLOGICAL CONTEXT

The research initiative was launched on a substantial corpus of engravings on limestone artefacts recovered during stratigraphic excavations at the Grotta di Santa Maria di Agnano (Ostuni – BR) [16].

Between 2015 and 2017, excavations were carried out in the western area of the Agnano cave. Beneath an Early Neolithic occupation layer associated with impressed and incised ceramics (5894–5709 calBC), a complex stratigraphic sequence dating to the Late Mesolithic was identified. Radiometric calibrated dating places this sequence within the second half of the 8th millennium BC [17].

The discovery of a limestone stone circle (Circle no. 3) exposed during the excavation of SU 81, followed by levels containing intentional accumulations of faunal remains (e.g., SU 87), suggests a distinctly ritual function for the area. This interpretation is further supported by the abundant presence of engraved limestone artefacts and incised bone fragments bearing schematic motifs that remind symbolic signs already attested at Agnano in the later phases of the Upper Palaeolithic.

The assemblage recovered from the archaeological investigations appears homogeneous mainly and consists of over 60 limestone pebbles bearing incised geometric-linear motifs. However, the quantity is difficult to assess due to the poor visibility of graphic traces on surfaces affected by carbonate alteration.

The limestone pebbles exhibit irregular volumes and surfaces, with heterogeneous textures and significant surface degradation (including erosion, carbonate encrustations, etc.). The engravings are defined by incised marks, often extremely faint – ranging from symmetrical to asymmetrical, shallow to deep – and present non-uniform graphic patterns. The frequent overlap of multi-directional strokes further complicates the systematic visualization of the graphic syntax under a single light source.

An experimental study was therefore initiated to assess

whether the combined use of high-precision photographic documentation and digital artificial visualization techniques could enhance the detection and analysis of the traces left by the tools used to execute the engravings.

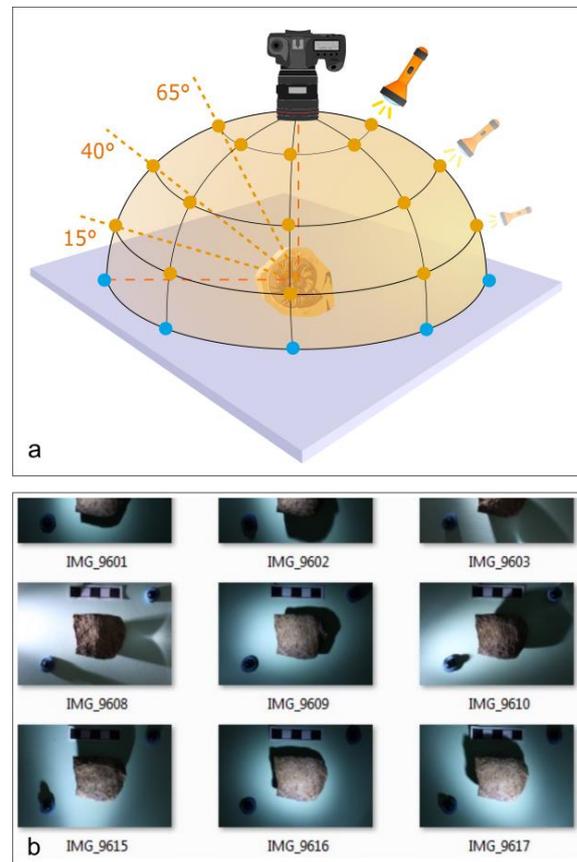


Fig. 2. Photographic acquisition method (a) and sample of processed images (b).

III. TOOLS AND METHODOLOGIES

The methodological refinement focused on a selected sample of eight decorated limestone artefacts, part of the artistic repertoire from the Early Holocene identified during the excavations at Santa Maria di Agnano [18]. In line with open-source workflows and low-cost instrumentation, a non-invasive image acquisition and processing technique was calibrated, based on polynomial surface mapping: Reflectance Transformation Imaging (RTI) (figure 2)[19].

The software processes a series of photographic images of a static subject captured under varying lighting conditions. The algorithm – initially developed at Hewlett

Packard Laboratories (PTM) [20] and later optimized through Hemispherical Harmonics mapping (HSH) by the University of California, Santa Cruz, in collaboration with the Cultural Heritage Imaging© foundation – encodes the reflectance properties of each pixel in the photographic frame. It then calculates the reflectance functions from the acquired data, enabling interactive and analytical visualization of the subject.

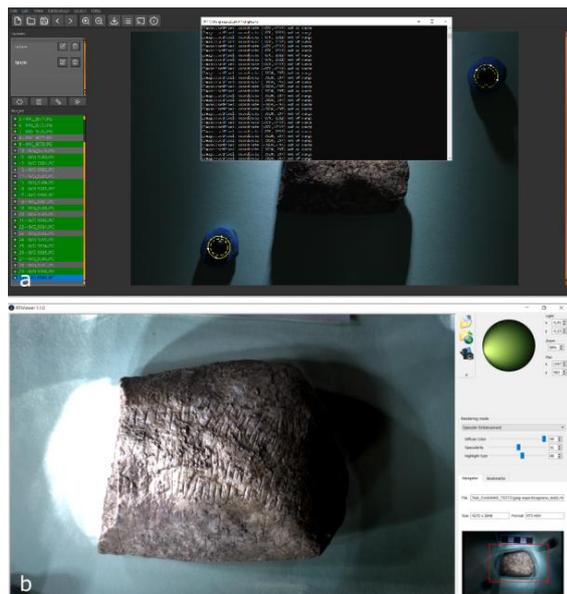


Fig. 3. a) RelightLab: sphere detection phase; b) RTIviewer: visualization in Specular Enhancement mode.

This study used the open-source software RelightLab as the primary platform for processing and rendering RTI datasets. Developed in 2021 by C. Wacker and collaborators at the Hochschule Mainz – University of Applied Sciences (Germany), RelightLab offers a user-friendly and efficient solution for Reflectance Transformation Imaging analysis, supporting both PTM and HSH rendering models (figure 3). The software facilitates the visualization of fine surface details by allowing users to relight digital artefacts interactively, and it provides advanced export options for integration into broader documentation workflows. Its accessibility and compatibility with low-cost imaging setups make it suitable for field applications and large-scale archaeological documentation projects.

During the acquisition phase, the photographic setup consisted of a laboratory stand to support and stabilize a digital camera (Canon EOS 1100D, E-FS 18–55mm), mounted on a custom-built light dome. To optimize the digital extraction of surface normals from each photo's incident light, a low-light environment was recreated

using a semi-rigid dome with a matrix of openings to position and manipulate an LED light source. For each RTI session, 36 images were captured (manual focus, EFL ~25mm, ISO 100; 12 MP, JPEG format), corresponding to the grid of equidistant light points within the dome's geodetic system (ranging from 15° to 65°), using a remote trigger. The average time per capture session was under ten minutes.

For the virtual-RTI experimentation, the technique was replicated on the polygonal meshes of three sample artefacts acquired via close-range photogrammetric survey (figure 4). In this context, the sequence of image frames required for the RTI simulation was generated within a 3D graphics environment (Blender), by creating a virtual light dome and rendering the object under varying light positions using an orthographic camera [21, 22].

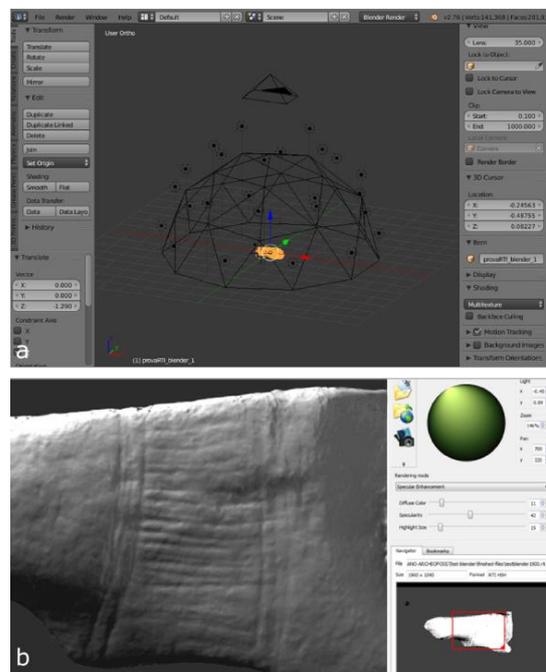


Fig. 4. a) Blender: virtual lightdome with orthographic camera and object mesh; b) RTIviewer: Specular Enhancement visualization mode of the v-RTI process.

IV. RESULTS

The multidisciplinary methodological approach and functional workflow of multi-lighting RTI analyses have supported a significant improvement in the rendering of greater detail compared to the empirical observation of complex surfaces from a photographic shot using

traditional methods, making it ideal for documenting subjects with generally regular profiles and for highlighting multiform microtraces and grooves [21][23][24].

Virtual interaction with the light source and rendering in simulated false 3D using digital environment visualization have allowed for an overall improvement in shapes and the most particular details, expanding the dataset to be analyzed: the contextual vision and the reading of further incomprehensible signs therefore allowed for the revision of the previously executed graphic documentation, balancing a high degree of representation clarity with a diffuse image-based luminosity [25][26].

However, one of the limitations found in applying the technique is identified in the lack of methodological flexibility in the photographic shooting phases: if the working process seemed expedited, the complexity of the volumes and the irregularity of the sample morphologies often hindered the reading of considerable portions of the reproduced surfaces, leading to a reformulation of the workflow with different angles and a reliance on compromise solutions.

The RTI technique reproduced in a virtual environment, on the other hand, although calibrated to the degree of accuracy of the scanning instrument used (macro photogrammetry, laser scanner, etc.), despite exhibiting the same intrinsic limitations of its application, proved to be replicable and multiscale: the application of the multi-lighting test on digital surfaces, in fact, in addition to streamlining the acquisition phases and ensuring their remote manipulation, could be replicated by overcoming the limitation of complex volumes, adapting the surfaces to the reading needs that are demonstrated each time.

The most interesting outcomes, in addition to the improvement in the graphic aspects, concern the possibility of initiating a further semiotic investigation into the paleographic dynamics of sign execution [12][26]. The advantage of interacting with and varying the orientation of the virtual light source allowed for a deeper understanding of the characteristics of the identified micro-traces, revealing valuable information about the complex morphological and dimensional variety of the recorded marks (*V-shape*, *U-shape*, *flat*, *bifid*, *multiple*, *codebar*, etc.). This information not only allows us to hypothesize the methods and tools used, but sometimes even suggests their profile and the directions of the incisions [27][28][29].

In this sense, the opportunity offered by virtual RTI to process normals calculated derived from polygonal meshes by photogrammetry, even with a low degree of geometric accuracy as in this case, has created the conditions for a qualitatively better analysis of digital surfaces and their processing, even when integrated with the results obtained from traditional processing methods

(such as for the radiance scaling algorithm)(figure 5a-d) [13][30].

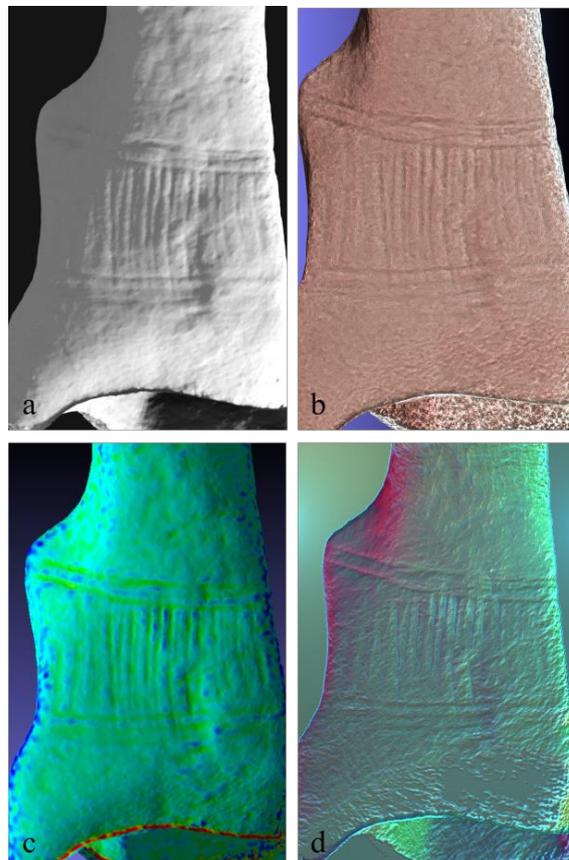


Fig. 5. Detail of an engraved pebble (SMA-test 9). RTIViewer: a) Normal Unshrap Masking; MeshLab: b) Lit Sphere Radiance scaling; c) Colorize curvature; Laigter: d) Normal map light-augmented.

V. CONCLUSIONS

Although limited to a small sample, this experimentation demonstrates that the RTI-technique represents a highly competitive and effective analytical methodology. It can be implemented with relatively low-cost instrumentation and an open workflow. The results confirm the high quantitative and qualitative standards of the reproduced markings, positioning the technique not merely as an alternative, but as a promising and innovative approach deserving further exploration. These findings also invite broader reflection on its potential for preserving and enhancing archaeological contexts.

Future research should expand the sample of engraved lithic supports from the Santa Maria di Agnano

stratigraphic sequence, enabling comparisons with other corpora, some of which remain only partially published [2]. The objective is to identify coherent and homogeneous elements relating to the "grammar of signs" used by Palaeolithic and Mesolithic hunter-gatherer groups in southeastern Italy.

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