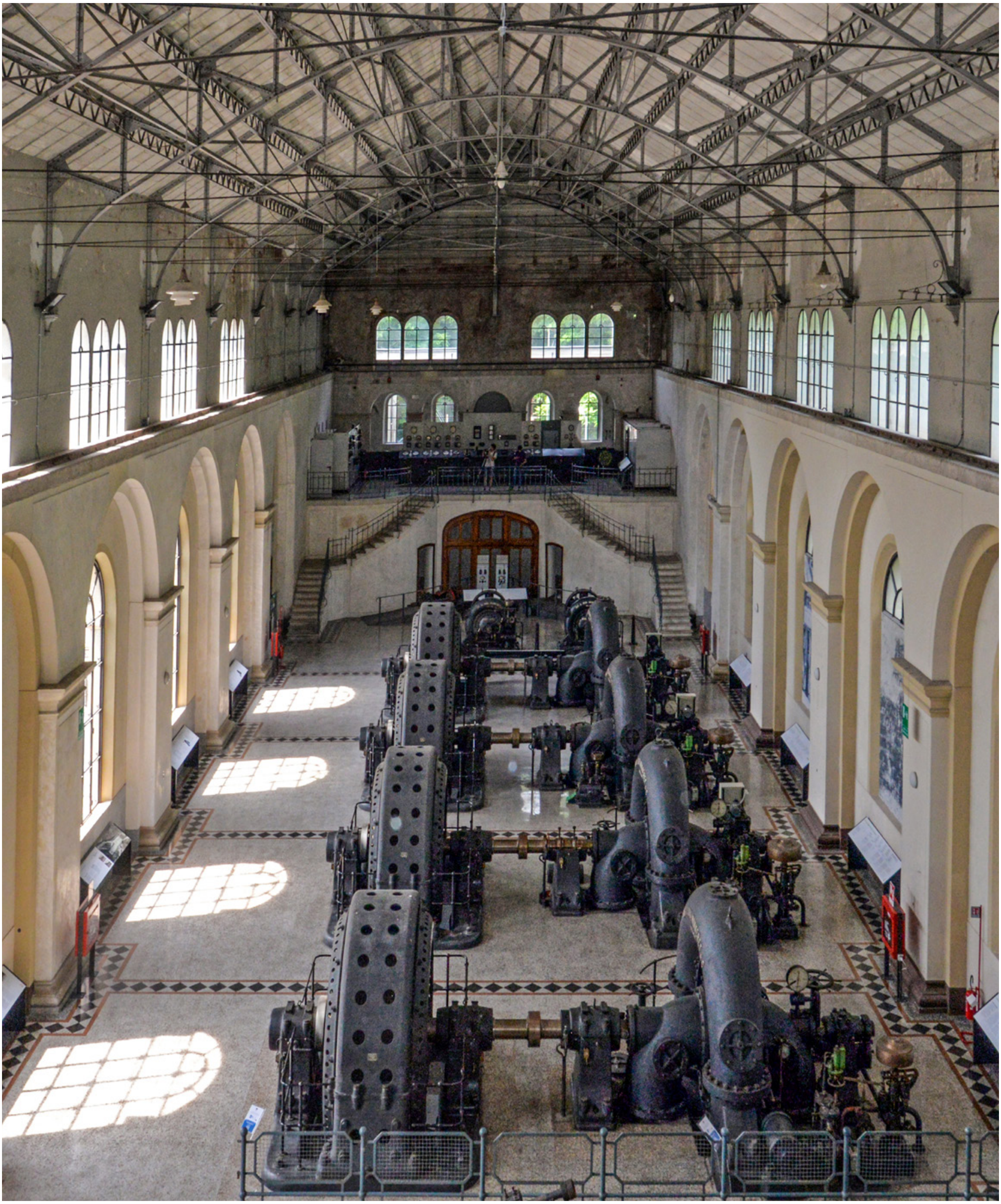

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# HOW DO VISITORS PERCEIVE THE ARCHITECTURAL HERITAGE? EYE-TRACKING TECHNOLOGIES TO PROMOTE SUSTAINABLE FRUITION OF AN ARTISTIC-VALUED HYPOGEUM

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**Highlights**

Sustainable strategies for Building Heritage should consider built environment conservation and adequate visitors' exploitation.
Hypogeum environments are significant contexts in this sense due to the visitors' impact on thermal conditions.
A conservation-based fruition model is tested through experimental tests in a hypogeum to evaluate visitors' engagement.
Visitors' perception of artifacts is investigated through eye-tracking technologies, while fruition paths allow detecting timing issues in hypogeum spaces.
The proposed fruition model allows a good visitors' engagement and the conservation of its natural thermal conditions.

**Abstract**

Sustainable strategies for Architectural Heritage reuse rely on preserving built environment features and maximizing visitors' engagement. Occupancy issues can cause the degradation of building materials and surfaces, especially in isolated built environments, like hypogeum. The visitors' presence affects indoor hygrothermal loads. Acceptable fruition models could provide number and timing for visitors' access, but behavioral patterns should be assessed to evaluate if conservation-based assumptions can provide adequate users' engagement. This work adopts technologies for detecting users' behaviors and perception, applying it to a hypogeum characterized by high-valued reliefs on sandstone surfaces. Visitors' numbers and times are defined to guarantee that thermal conditions do not exceed hypogeum natural fluctuations. Given this fruition model, in-situ experiments are performed to assess visitor's perception of high reliefs and fruition patterns. Perception is investigated through a wearable eye-tracking system to point out which artifacts attract more attention and how. Fruition patterns are assessed in terms of users' paths and engagement time in the hypogeum areas. Results show that the users' attention is focused on better conserved and lightened high reliefs, suggesting the importance of lighting-design strategies for hypogeum reuse. The proposed fruition model can ensure satisfactory users' engagement while guaranteeing adequate hypogeum thermal conditions.

**Keywords**

Building Heritage, Sustainable fruition, Users' behaviours, Eye-tracking, Hypogeum.

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## 1. INTRODUCTION

Preservation and touristic exploitation of the Architectural Heritage often seem to be two contrasting items because of their challenging conflicts, and specific sustainable design strategies should be developed by considering both built environment features and visitors' fruition [1, 2]. The preservation of the built environment features implies the reduction and contrast of critical conditions in Architectural Heritage due to the massive or permanent presence of users inside the built environment itself [2–4]. Either the users' presence and the installation of building systems and components to support the visitors' access and fruition in a comfortable condition (e.g., lighting, HVAC systems; insulation materials for Heritage energy efficiency) [5] could lead to a variation of indoor environment parameters [6, 7]. Although some of these building systems (e.g., HVAC) could restore adequate indoor conditions, efforts due to their implementation in the Architectural Heritage could lead to the loss of key features of the built environment itself, as well as to high implementation costs [2, 5, 8]. Such issues become critical in specific and sensible environments such as underground structures. On one side, underground environments can have significant artistic, historical and cultural values, being hydraulic or military works, but, more frequently, civil and cult works often characterized by valued surfaces and artifacts [3], such as paintings, graffiti, engravings, and high reliefs, often carved in the hypogeum stoned. On the other side, their microclimatic conditions are almost constant in both terms of indoor temperature and relative humidity because of their isolation from the outdoor and their generally reduced space dimensions [3, 6, 9]. As for man-made above-ground structures [7, 8], when visitors come into a hypogeum, their hygrothermal loads can sensibly alter the indoor microclimate [3, 6, 10]. Conservation problems can be hence due to increased bio-colonization, biodegradation, and salt crystallization, especially under massive and constant exploitation conditions and considering hygroscopic building materials, such as wood and stone surfaces [7, 11]. These materials suffer from water absorption and desorption, thus being prone to biological deterioration phenomena, especially when the exploitation-induced hygrothermal fluctuations are higher than the natural ones. Then, such conditions cause expansion, drying up, and fragility increase of surface layers of the materials.

Microclimate monitoring-based approaches and simulation models could be used to define fruition models that can guarantee the Architectural Heritage features preservation by also focusing on these vulnerable building materials and artifacts hosted in the built environment [7, 8, 12]. Such models can define the possibility to implemented building systems for microclimate control and to perform conservation interventions on the artifacts, but also rules for visit timing, number of allowed visitors (per visit, per day), and recovery timing between different visits (to restore natural and adequate microclimate conditions. Nevertheless, these fruition models can be effectively defined as sustainable if: (1) from the stakeholders' perspective, positive economic and social impacts can be achieved [1, 13]; (2) from the visitor's perspective, they can ensure a satisfactory engagement level towards spaces and objects of the built environment [14, 15]. Current limitations mainly relate to the visitors' engagement assessment, which is often based on qualitative surveys and does not actually involve quantitative measurement tools [14]. Recent works have shown how eye-tracking technologies can evaluate the users' perception of the Architectural Heritage since they allow detecting "where and how" (e.g., in which way, for how many time) the visitors' attention are attracted by its artifacts in a quantitative manner [15, 16]. These technologies can help stakeholders to evaluate fruition times and behavioural patterns of visitors [17, 18], since experiments can be easily carried out by asking users to wear eye-tracking glasses and freely move in the environment [17], to use fixed eye-tracking systems, e.g., standing in front of a single artifact or painting [19].

In view of the above, this study aims at assessing how a proposed fruition model can be considered sustainable for both preservation and visitors' exploitation perspectives. A hypogeum environment is considered to this end, in view of its vulnerability-affecting features in terms of building materials conservation. Eye-tracking technologies and related analysis methodologies are adopted, and in-situ experiments are carried out to detect the visitors' behavioural patterns and engagement levels considering an imposed fruition model that minimizes the hygrothermal fluctuations inside the hypogeum. Finally, experimental-based suggestions on how to improve the visitors' experience and control of indoor conditions are provided by means of building systems.

## 2. METHODS

This work was organized in the following phases. Firstly, a significant case-study hypogeum was selected, and a fruition model was proposed to minimize the effects of visitors' fruition on the indoor environmental conditions while exploiting the underground spaces for touristic purposes (Section 2.1). Then, experiments with volunteers were performed by using techniques for behavioural patterns detection, i.e., by eye-tracking data (Section 2.2). Such experiments allowed understanding how people moved and perceived the hypogeum and its artifacts, as well as if they were satisfied with the imposed fruition model (Section 2.3).

### 2.1. CASE STUDY DESCRIPTION AND PROPOSED FRUITION MODEL FOR HYPOGEUM EXPLOITATION

The hypogeum environment of Palazzo Campana (Osimo, AN) was selected as a significant case study for the analysis of visitors' behavioural patterns. Its walls, values, and domes, dug in the building subsoil, are characterized by artistic-valued high reliefs carved in the sandstone. These high reliefs have been suffered a severe state of degradation during the time also because of the non-regulated fruition model by visitors. Users' presence in the "isolated" environment of the hypogeum altered the natural thermal conditions, which also provoked degradation-increasing rapid thermal fluctuations. In particular, this work focuses on visitors' use of the main corridor of the hypogeum (compare Figure 1 and Figure 2) because of its significant layout (mainly characterized by a main vaulted space and a centra dome) as well as the artistic value of the hosted artifacts, and so its potentiality in view of touristic exploitation. The main corridor was equipped with two LED light fittings (20W of emitted power per lamp) applied at the start of the corridor (i.e., area 1 in Figure 2) and into the circular hall (i.e., area 7 of Figure 2), thus providing illuminance values ranging from 30 to 60 lux at the ground level.

According to previous experimental tests in the case study environment [12], the fruition model considers that 10 visitors can remain in the hypogeum for 10 minutes. Given the visitors' presence and the switched-on lights, this combination ensures that the indoor temperature variations in the hypogeum will not exceed the natural fluctuations range (equal to 0.56°C). Then, a recovery time of 15 minutes is imposed to allow restoring the original indoor temperature conditions. During the recovery time, no visitors are not allowed to enter, and the lighting system is switched off. Although the fruition model fits with conservation issues, tests on visitors' behaviours have not been already performed to verify the visitors' engagement and enjoyment.

### 2.2. EXPERIMENTS ON VISITORS' BEHAVIOUR

In-situ experiments involved 10 visitors, who declared that they had never entered the hypogeum before the tests. Only one visitor per time was engaged in the test to focus the users' visual stimuli to those of the built environment and its artifacts.

At the start of each test, the visitor was asked to wear the Tobii Pro Glasses 2 (https://www.tobiipro.com/siteassets/tobii-pro/brochures/tobii-pro-glasses-2-brochure.pdf/?v=6, last access: 17/04/2021). This wearable eye-tracking system is composed of a pair of glasses with 4 eye cameras to detect the eye's movement according to Pupil Centre Corneal Reflection techniques. The gaze sampling frequency of the eye cameras is 50 Hz [15]. A full HD wide-angle frontal camera and an integrated microphone are mounted on the glasses to record the view scenes of the user without any movement restriction. Data from eye cameras and the wide-angle camera are then saved on a wearable recording unit, which can communicate with the controller software via wireless, which allows calibrating the wearable glasses to the users' eyes features (to detect their movement), starting and stopping the data acquisition, and monitoring the test in real-time. Data are then analysed by Analysis Software Tobii Pro Lab to trace quantitative (e.g., fixation time, fixation number per objects or area of interest) and graphical (e.g., heat maps of fixation data, order of fixations overlapped to the scenes views) metrics of visitors' attention [16].

After he/she had worn the glasses and the calibration step was performed, the visitor entered the main corridor starting from area 1 in Figure 1, and he/she was allowed to freely move in it to observe the layout and the artifacts. The visit lasted for 10 minutes, according to the fruition model in Section 2.1. The visitor's attention and fruition patterns were recorded during the test. At the end of the experiment, each visitor was asked to fill a satisfaction questionnaire. A 5-items Likert scale (1=strongly disagree; 5=strongly agree) was used to investigate if: a) the visiting time was adequate to ensure a satisfactory enjoyment of hypogeum layout and artifacts in the main corridor (e.g., spatial development, figures, and details); and b) if they felt comfortable with the eye-tracking testing procedure.

### 2.3. CRITERIA FOR VISITORS' BEHAVIOUR ANALYSIS

Thanks to the frontal camera of the eye-tracking system, the motion paths of visitors inside the hypogeum were firstly assessed. Walls, vaults, recesses, and the dome of the circular hall were divided into objects for the analysis of visitors' attention. Each object represents one of the high reliefs. In particular, for each object, the visitors' attention has been calculated depending on their fixation in terms of duration $A(o,t)$ [%], as shown by Equation 1, and of the number of fixation $A(o,f)$ [%], as shown by Equation 2 [16, 20]:

$$A(o,t) = \frac{Tg,o}{Tg,max} = \frac{\sum_v Tg,o,v}{Tg,max}\ [\%] \qquad \text{[Equation 1]}$$

$$A(o,f) = \frac{Fg,o}{Fg,max} = \frac{\sum_v Fg,o,v}{Fg,max}\ [\%] \qquad \text{[Equation 2]}$$

where $Tg,o$ [ms] and $Fg,o$ [-] respectively are the overall gaze time and the overall number of fixations considering the object $o$, $Tg,o,v$ [ms] and $Fg,o,v$ [-] respectively are each visitor $v$'s gaze time and each number of fixations considering the object $o$, and $Tg,max$ [ms] and $Fg,max$ [-] respectively are the maximum $Tg,o$ and $Fg,o$ for the tested environment. An object fixation has been considered if the related single gaze event is equal to or longer than 560 ms [21]. Input data for Equations 1 and 2 were provided according to Analysis Software Tobii Pro Lab.

The higher $A(o,t)$, the higher the engagement and attention towards a detail of the object. The higher $A(o,f)$, the higher the number of occasions in which the visitor was attracted by the object and the higher the visitor's interest in it. As a consequence, objects with higher $A(o,t)$ and $A(o,f)$ can be defined as dominant objects for the built environment with respect to the visitors' engagement [16, 20]. Heat maps can be applied to dominant objects to examine the specific areas that had attracted the most the individual's attention. Heat maps in terms of gaze time have been analyzed in an aggregate manner, that is, considering the whole number of visitors, through the Analysis Software Tobii Pro Lab. Furthermore, each object was associated with a qualitative conservation level between: 0 (no visible reliefs, including recesses), 1 (very poor), 2 (average), or 3 (good). Then, Spearman's rank correlation coefficient [22] was calculated to measure the strength of association between pairs of $A(o,t)$, $A(o,f)$, and conservation level (including and excluding the recesses). The Spearman's rank correlation coefficient was chosen because it allows tracing the association between continuous (i.e., $A(o,t)$, $A(o,f)$) and ordinal (i.e., conservation level) data, also in case of non-normal distribution.

The hypogeum was also divided into areas of interest $a$ [23] for the visitors according to its plan layout (compare Figure 1), that is, considering their geometrical features and the configuration of related recesses. Considering the visit duration of 10 minutes, the engagement percentage in the area of interest $E(a)$ [%] represents the overall percentage of time during which each visitor remains in each given area of interest and focuses his/her attention on the related artifacts.

Then, the average engagement time $TE(a)$ [s] has been calculated for each area of interest as the multiplication between $E(a)$ and the overall visiting time (10 minutes, so 600s). For each area of interest, the maximum number of allowed individuals *V(a)* [persons] is calculated by considering fluid fruition conditions and motion flows (1.4m²/person) [24]. The overall engagement time *OE(a)* for a given area of interest was calculated according to Equation 3:

$$OE(a) = TE(a) \cdot \frac{Gr}{V(a)} \; [s] \qquad \text{[Equation 3]}$$

where *Gr* [persons] is the overall number of persons allowed per visit (i.e., 10 persons according to the proposed fruition model in Section 2.1). *OE(a)* also expresses how long the area of interest is used by the visitors, at most. *OE(a)* should be hence always lower than the visiting time (i.e., 600s according to the proposed fruition model in Section 2.1) to ensure that all the visitors can enjoy the area and the related heigh reliefs.

Finally, the visitors' satisfaction and comfort with the eye-tracking system were evaluated according to the questionnaires data by evaluating if the mean and median values of responses can be associated to positive levels in the Likert scale (>3).

## 3. RESULTS

### 3.1. VISITORS' BEHAVIOUR

According to the analysis of frontal camera videos, three main motion patterns in the 10 minutes-long hypogeum visits were retrieved. 40% of visitors walked through the main corridor only once from the starting point (area of interest 1 in Figure 2-C) to the ending one (area of interest 8 in Figure 2-C). In this way, they looked only once at each object, mainly moving in a zigzag. 60% of visitors walked from the starting to the ending points of the corridors and then returned to the starting point again, mainly moving along a straight line (40% of the whole visitors' sample). 66% of these visitors firstly focused their attention on one side of the corridor when moving towards the corridor ends, and then were engaged in the other side while returning to the starting point. Finally, 33% of these visitors decided to move towards the corridor end and take an overview of the hypogeum and then returned slowly to the starting point, being deeply engaged in the fixation of the objects.

Figure 1 shows the visitors' attention in terms of *A(o,t)* and *A(o,f)*, for each of the considered objects, that are the high reliefs on walls, vaults, the dome, and recesses. Figure 2 traces the related *E(a)* values, including significant views of the main high reliefs in the hypogeum. Results show how *E(a)* grows with *A(o,t)* and *A(o,f)*, thus remarking the importance of fruition patterns on objects' attention also in terms of use of the hypogeum areas. Reasons for differences in space fruition and attention results are discussed below, considering the eye-tracking

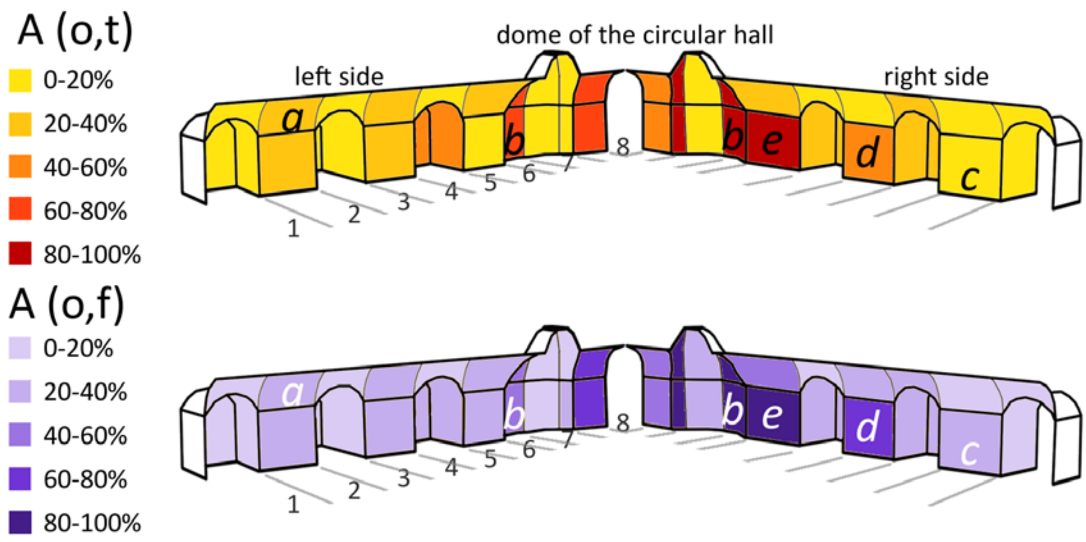



Fig. 1. *Visitors' attention on the hypogeum identified objects, in terms of attention time A(o,t) and fixation number A(o,f). Letters refer to Figure 2 high reliefs, while numbers (and related lines on the walls and the floor) refer to areas of interest in the upper part of Figure 1.*

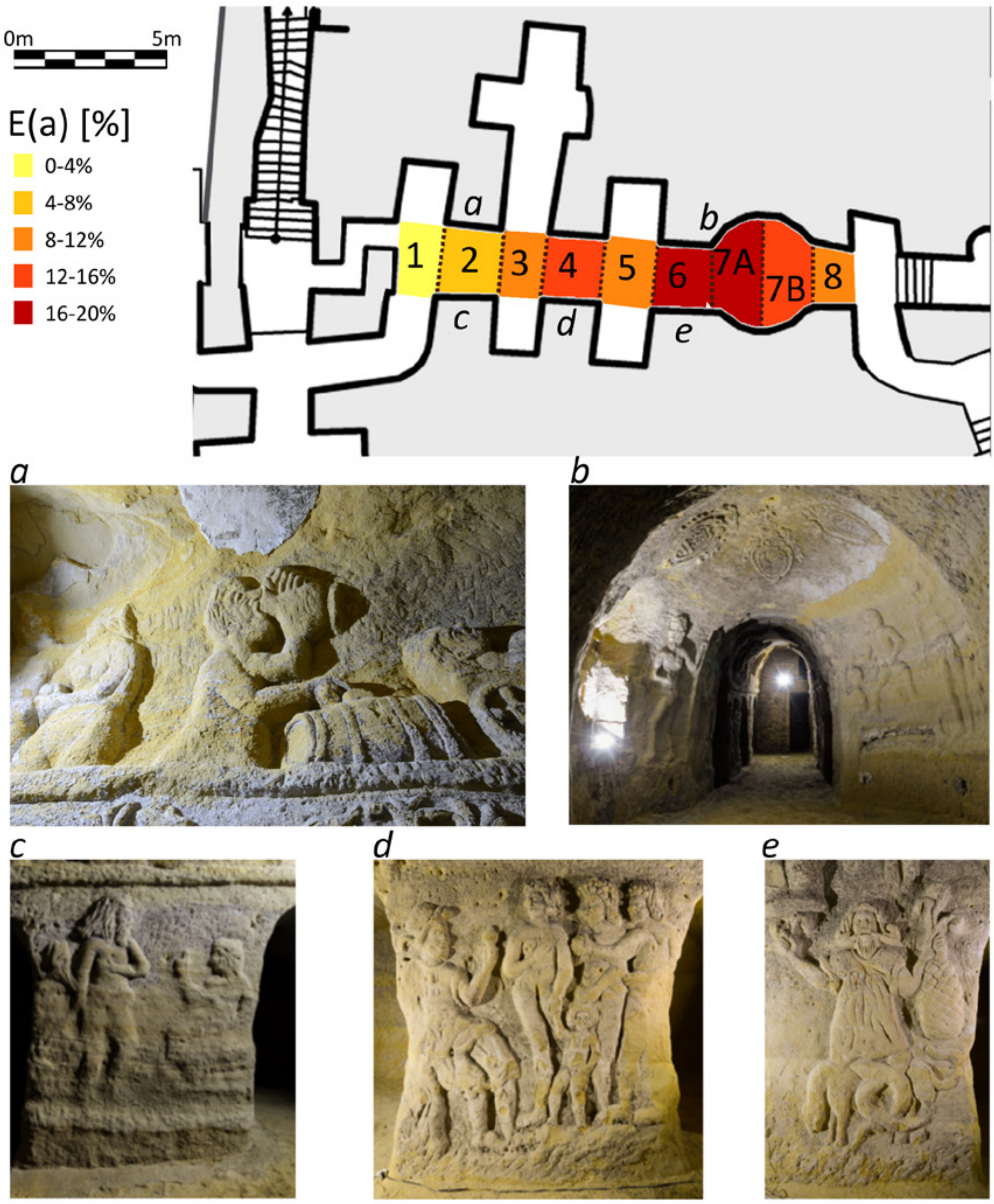



Fig. 2. *Engagement of visitors in the main corridor of the Palazzo Campana hypogeum: on the top, plan of the corridor including the percentage in the areas of interest E(a) [%], as well as the identification of the position of significant-high reliefs (letters in italics) and of the numbered areas of interest, both according to Figure 1 codes; on the bottom, photographs of significant-high reliefs according to the plan identification codes.*

data and thus confirming how wearable eye-tracking systems are capable tools to detect behavioural patterns in space fruition by visitors [15, 17, 25].

Firstly, results show that, by normal standards and in general terms, the association between the considered pairs of variables in Table 1 would be considered statistically significant according to the coefficient as well as the related 2-tailed p values ($<0.05$). In particular, a strong positive association ($\geq 0.800$ [22]) could be observed for *A(o,t)* and *A(o,f)*, as well as for both these eye-tracking-related data and the conservation level of the objects, excluding the recesses. Then, the higher the qualitative conservation level of the object, the higher the interest of the visitors in terms of both fixation time and number. For instance, the high relief in Figure 2-e (conservation level=3) had *A(o,t)*=86% and *A(o,f)*=95%, while the one in Figure 2-c (conservation level=1) had *A(o,t)*=13% and *A(o,f)*=26%.

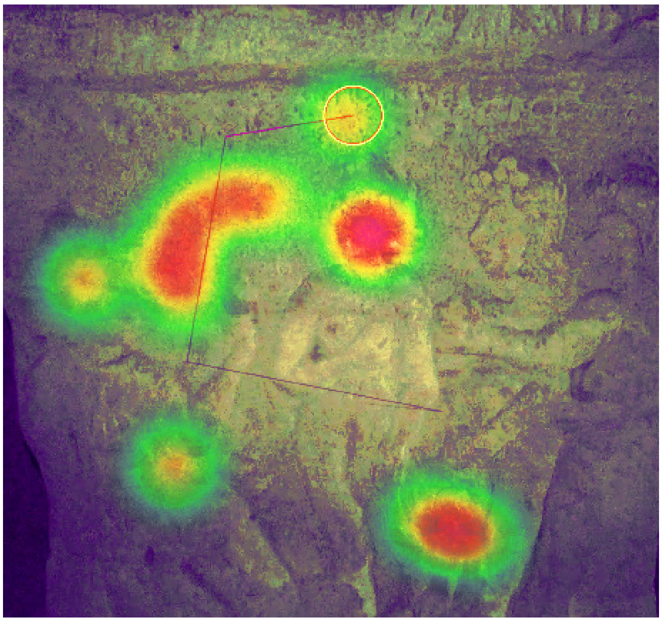
| | A(o,t) | A(o,f) | conservation level | |
|---|---|---|---|---|
| | | | recesses included | recesses excluded |
| A(o,t) | 1 | 0.977 (<0.001) | 0.418 (0.009) | 0.816 (<0.001) |
| A(o,f) | 0.977 (<0.001) | 1 | 0.408 (0.011) | 0.800 (<0.001) |

Tab. 1. *Spearman's rank correlation coefficients for the tested pairs. In round brackets, the 2-tailed p values are shown.*

Meanwhile, the visitors seemed to be mainly engaged with objects characterized by higher light intensity (i.e., the circular hall as in area 7 of Figure 1 and Figure 2-b where the illuminance at the ground level was about 60 lux). High reliefs characterized by strong effects of light and shadow seem to be preferred for the visitors' engagement, as in the example of high reliefs in the area of interest 7A, shown by Figure 2-b. The object placed on the left side of the circular hall (Fig. 2-b on the right) had about -20% of *A(o,t)* and more than -30% of *A(o,f)* with respect to those on the right side of the hall (Fig. 2-b on the left), according to Figure 1. In fact, the high reliefs on the right side were characterized by glancing light, which enhanced the depth of the reliefs, while the ones on the left side were characterized by full light.

Figure 3 shows, on the left, the Analysis Software Tobii Pro Lab results concerning heat maps of aggregate gaze time (i.e., considering the whole number of visitors), for the high relief in Figure 2-d, which is one of the dominant objects of the hypogeum as shown by Figure 1 and have a good conservation level (equal to 3). The areas with the warmer colours represent the points where the visitors focused more in terms of time. It is, therefore, possible to recognize how the greatest attention is concentrated mainly on the faces of the human figures, not only on those that dominate the scene but also on minor figures such as the child portrayed below (points "a" in Fig. 3 on the right). The gestures of the human figures in the scene are other relevant details for the visitor's attention (point "b" in Figure 3 on the right).

*OE(a)* was finally calculated for each area of interest. Considering the contemporary presence of 10 individuals, areas of interest 7A and 8 (see Fig. 2-b) should be occupied for the longest time. Anyway, both of them have *OE(a)*<600s (i.e., about 350s for area 7A with 3 people in it and about 360s for area 8 with 2 people in



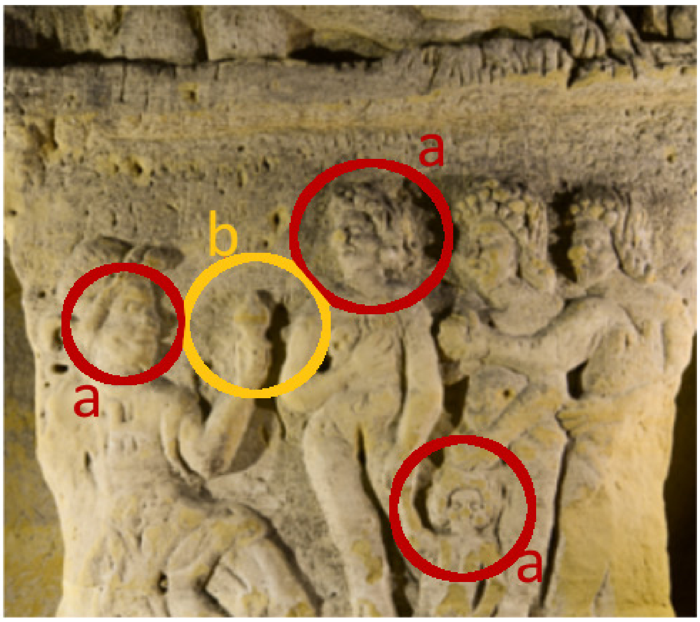



Fig. 3. *Example of eye-tracking-based analysis for a dominant high relief (letter d in Figure 1 and Figure 2): on the left, the heat map of visitors' attention time; on the right, a view of the high relief with the related highest areas of engagement ("a"/in red-faces and "b"/in yellow-gestures of the human figures).*

it), thus allowing visitors to have enough time to enjoy the related objects during the 10 minutes-long visit in comfortable density conditions. Questionnaires results underlined how the visitors were generally pleased with the fruition model (mean vote: 4.4, st, dev.: 0.6). They also felt comfortable with the testing procedure and the eye-tracker (mean vote: 4.7, st. dev.: 0.4), thus confirming the capabilities of the used glasses for in-situ tests.

### 3.2. INSIGHTS ON HYPOGEUM FRUITION

Although the 10 minutes-long visit can ensure an adequate engagement by users while guaranteeing adequate conservation levels of the high reliefs, some suggestions on a possible reorganization of the hypogeum facilities can be proposed. Previous experiments with 10 people in the hypogeum traced variations in the indoor temperature near this area, thus demonstrating how the visitors' presence-induced variations were lower than the natural indoor fluctuations, as shown by Figure 4 [12]. Nevertheless, an intelligent control system of indoor environment conditions could monitor the variations during the visiting time, thus ensuring that an adequate alarm could be sent to the hypogeum stakeholder in case of values over the threshold.

A possible easy-to-apply strategy could be the implementation of a walkway, as in the example scheme of Figure 5. The use of a walkway could increase the separation distance between the visitors and the high reliefs to protect them from users' accidental movements, and it could be equipped with temperature and humidity sensors, mainly displaced near the walls, so as to monitor the indoor environment conditions and the sandstone state [12]. Corrective actions could be applied if natural fluctuations could be overcome during a visit, depending on the visit access and timing as well as on the visitors' presence. In this way, a dynamic fruition model mainly based on the temperature trends could be employed to overcome the strict time-based one proposed by this work and additionally increase the visitors' satisfaction. In particular, such sensors should be mainly placed near areas of interest 6 and 7, because they seem to attract more visitors and for a longer time. The visitors' presence control could also retrieve possible individual actions against the high reliefs (e.g., act of vandalism). Finally, results suggest that light fittings should be relocated to increase the shadow contrast of high reliefs and thus scattering the visitors' attention towards all the objects in the main corridor. A glancing LED light system could be implemented into the walkway, e.g., being placed at the ground level.

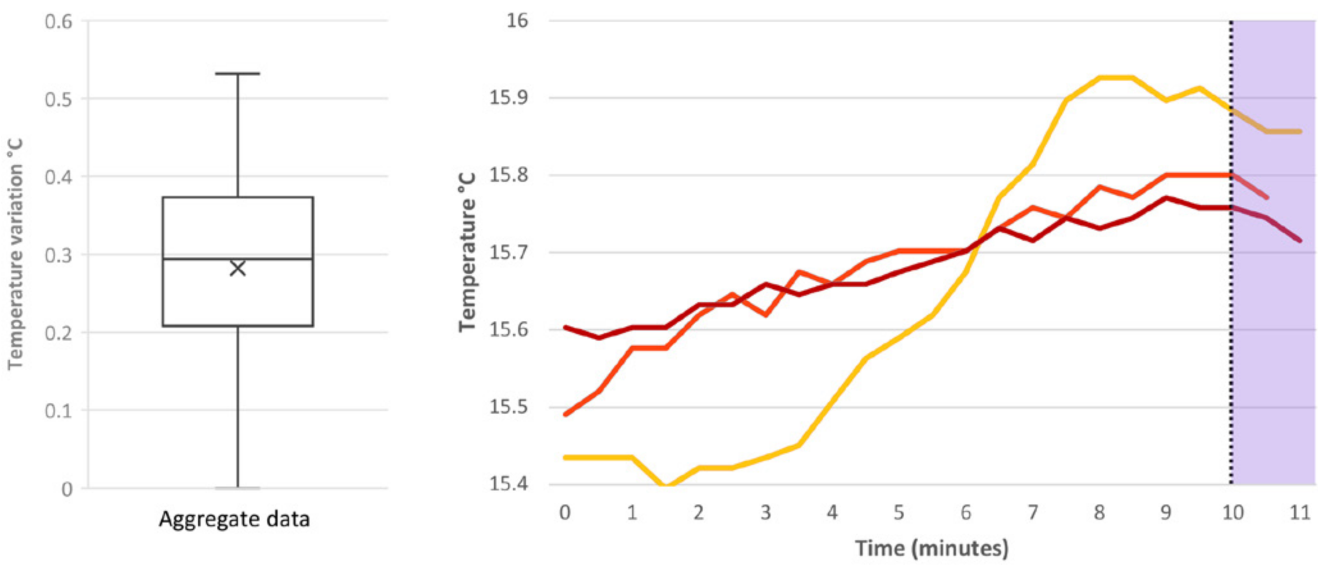



Fig. 4. *Temperature data near the areas 6 and 7 during a visit of 10 users for 10 minutes: on the left, variation of temperature; on the right, temperature values over the time, for three different visits (different colored lines) including the first minute of the recovery time (violet area). Data adapted from [12].*

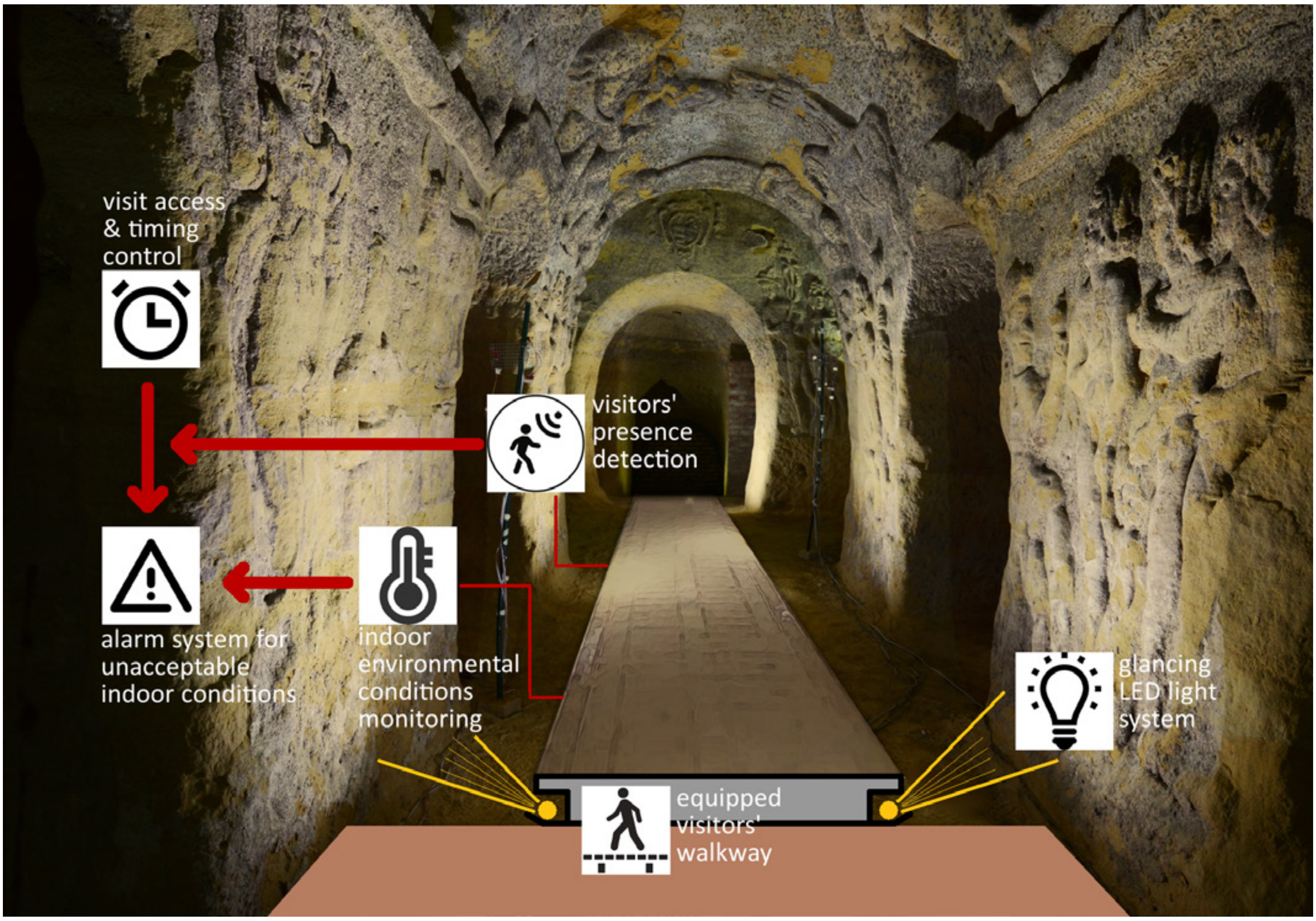



Fig. 5. *Scheme of visit walkway and control system for the main corridor of the hypogeum.*

## 4. CONCLUSIONS

This work provides an experimental-based methodology for assessing the sustainability of touristic exploitation of Architectural Heritage, such as artistic and cultural valued hypogea, in which the visitors' presence could lead to artifacts and surfaces conservation problems due to induced hygrothermal variations. The sustainability purposes are both achieved considering the artifacts preservation and an adequate visitors' engagement. The visitors' fruition model is derived depending on admissible indoor microclimatic conditions, being supported by experimental tests. The visitors' engagement and behavioural patterns in the hypogeum according to the selected fruition model are assessed through eye-tracking technologies.

Results show the peculiarities of the fruition patterns in the considered case study, which is mainly characterized by high-valued reliefs that suffered a severe state of degradation during the time also because of the non-regulated fruition model. In particular, as shown by correlation analysis, prominent roles for visitors' engagement are played by the conservation level of the artifacts, as well as by the lighting fittings feature. In particular, high reliefs intensified by more sensible light-shadow contrast increase their visitors' attractiveness. Nevertheless, insights on the capabilities of the eye-tracking-based methodology and experimental-based suggestions on how to re-organize or implement new facilities in the hypogeum could provide interesting preliminary remarks to be applied in other scenarios and contexts. In particular, dynamic monitoring systems could be implemented into the Architectural Heritage to allow (small) variations in the visitors' fruition model to increase their engagement while controlling that natural fluctuation can be respected. Additional technologies for visitors' fruition times and behavioural patterns (e.g., individual and collective tracking) could be combined both to support the dynamic monitoring system and to increase the sample of experimental analysis in real-world environments. From this perspective, future works should also extend the proposed approach to other scenarios of the Architectural Heritage (e.g., museums, exhibition spaces, churches) that require optimization of visitors' accesses and flows in terms of both environmental conditions and fruition schemes. The proposed methodology can be applied to different fruition models to evaluate the best exploitation-engagement-conservation combinations, and thus blending perspectives and needs of stakeholders, visitors, and Heritage. In addition, its application towards degradation issues due to hygrothermal factors, the proposed approach could also be used to solve other fruition problems, such as safety-related ones (e.g., emergency safety such as fire safety, pandemic conditions control), in historical built environments open to the visitors with structural or spatial limitations (e.g., small rooms, towers, crypts, passages at height, tunnels) and that were not designed for constant and numerous users' flows and presences.

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