# Vis4Heritage: Visual Analytics Approach on Grotto Wall Painting Degradations

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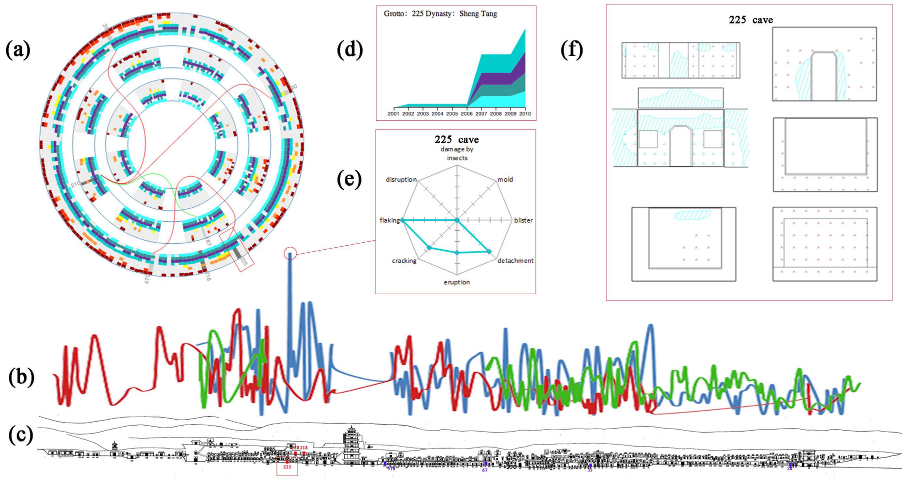


Fig. 1. Interactive Visual Analytics on Wall Painting Degradations of Dunhuang Mogao Grottoes. (a) Overall site-level degradation visualization. The correlated caves are highlighted when cave 225 is selected; (b)Aggregated degradation visualization of caves in different floors in which spatial clustering patterns are obvious; (c) An illustrated Dunhuang Mogao Grottoes spatial profile; (d) Temporal degradation changes visualization; (e) Radar visualizations of high-dimensional degradation data; (f) Cave-scale degradations are visualized in glyphs and orthographic views.

**Abstract**—For preserving the grotto wall paintings and protecting these historic cultural icons from the damage and deterioration in nature environment, a visual analytics framework and a set of tools are proposed for the discovery of degradation patterns. In comparison with the traditional analysis methods that used restricted scales, our method provides users with multi-scale analytic support to study the problems on site, cave, wall and particular degradation area scales, through the application of multidimensional visualization techniques. Several case studies have been carried out using real-world wall painting data collected from a renowned World Heritage site, to verify the usability and effectiveness of the proposed method. User studies and expert reviews were also conducted through by domain experts ranging from scientists such as microenvironment researchers, archivists, geologists, chemists, to practitioners such as conservators, restorers and curators.

**Index Terms**—Cultural heritage, wall paintings, degradation, visual analytics

## 1 Introduction

Grotto fresco site is an important part of cultural heritage category in the world there are some famous caves with precious ancient wall paintings and other culture relics. Many famous UNESCO World Heritage sites are renowned for their ancient wall paintings, including the Complex of Koguryo Tombs, the Bamiyan Valley, Ajanta Caves, Quseir Amra, Altamira, and Dunhuang Mogao Grottos. The values of these wall paintings are far beyond the aesthetics of being art works, and they contain invaluable information about the contemporary society. However, these precious wall paintings are in danger. They are suffering from damage and deterioration problems. The impacts of damage and deterioration are from physical, chemical or biological aspects, including the result of natural weathering, environmental deterioration and human activities [1, 2, 19]. Visually these paintings are cracked, flaked, faded, disrupted, detached (pigment detachment and ground layer detachment), powdered and mildewed [46], as shown in Fig.2.

Cultural heritage studies are inherently with multi-discipline and analytical nature. Different domain experts have different views of these cultural entities based on their expertise and disciplines. However, many current analysis and investigation tasks are subjective based on the observations and impressions. Increasing volume of data have been captured, collected, archived, and recently stored in databases. These data are information about the wall paintings themselves, the degradations and corresponding impact factors. Almost


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all conservation experts, such as conservators, scientists, curators and operators, need to analyse, visualize and model the cultural heritage degradation information quantitatively.

Currently, however, most of concerns from experts are focusing on the status diagnosis, impact modeling, damage estimation, rational and scientific maintenance interventions and monitoring actions. However, the analysis, visualization, and understanding of the degradations are very challenging due to many reasons. Firstly, the complexity of degradations is partly due to the complicated structure of layered wall painting, which is consists of support layer, ground layer and paint layer. The support layer is covered by the ground layer made by earthen plaster with a mixture of clay, sand, and plant fiber. The paintings were drawn on the ground layer as line drawings filled with mineral pigments and organic colorants. Secondly, the data are of heterogeneous, multi-dimensional and multivariate nature, due to the diversity of data capture and description. Thirdly, the degradation mechanisms are complicated, often due to the combination of many factors. Fourthly, many wall paintings resided in cultural heritage sites have experienced a long history, perhaps a few hundreds years old, before they were discovered. In comparison with their thousands years of lives, the time they have been monitored and recorded is relatively short. The information and data which can be used to study their degradations, especially the formation processes and mechanisms, are very limited. Finally, the degradations have different characteristics, some are permanent and more stable, but others are more temporary and active.

Although Deufemia [11] and Inkpen [25] have developed their methods for collecting, analyzing, visualizing, and modeling the cultural heritage information. They are not designed for cultural heritage conservation applications. These methods are either for archaeological applications, or using generic visualization systems such as Geographical Information System (GIS) based methods. Little effort has been devoted to the customized visual analytics techniques and tools for the cultural heritage conservation studies. Furthermore, to the best of our knowledge, no specific approach for analyzing and visualizing of wall painting degradations has been developed so far.

Our research context is visual analysis of the wall painting degradations. The main goal is to identify and understand the degradation patterns of the wall paintings to facilitate the exploration of spatial and temporal degradation analysis for assisting cultural heritage experts to preserve the grotto wall paintings. This can be done by using the regular field survey and degradation tracking data. Our proposed approach supports the cultural heritage domain experts to do their analyses in an intuitive and efficient way. First, the visual analytics framework is designed to integrate a hypothesis testing methodology and an iterative observation-hypothesis-investigation process. The experts are very familiar with this method in their analysis and investigation tasks. Second, traditional investigation methods are mostly subjective. By cleaning and normalizing the unstructured survey and inspection data into structured and quantitative formats, our method can analyze the degradations in a quantitative way, and visualize the spatial and temporal degradation patterns. The approach and tools are essential for policy makers, local heritage owners and managers, for instance, the optimization of monitoring plan, intervention treatments, and preventive conservation strategies and measures.

Our main contributions are summarized as follows:

1) Proposed Vis4Heritage, a visual analytics framework for discovering the wall painting degradation patterns.

2) Developed a set of analytic and hypothesis verification tools for cultural heritage domain experts.

3) Proposed a new approach to support the multi-resolution degradation analysis. Comparing to traditional analysis methods on limited scales, our method can be used to explore the degradations on the site, cave, wall and particular degradation area scales.

4) Conducted case studies to test several basic hypotheses with the real data. Expert reviews are also executed to evaluate our methods, by domain experts ranging from micro-environment researchers, archivists, geologists, chemists, conservators, restorers and curators.

Our research is conducted in a renowned World Heritage site, Dunhuang Mogao Grottoes. It is also adaptable to the study of other grotto wall painting sites. It is believed that these kinds of techniques can also be used in the analysis of rock arts degradations [37] since they are facing to the similar problems.

The rest of this paper is structured as follows. We first review the background and previous work. We then proceed by presenting our approach. Case studies and expert review methods are used to evaluate our approach, and finally we draw our conclusions.

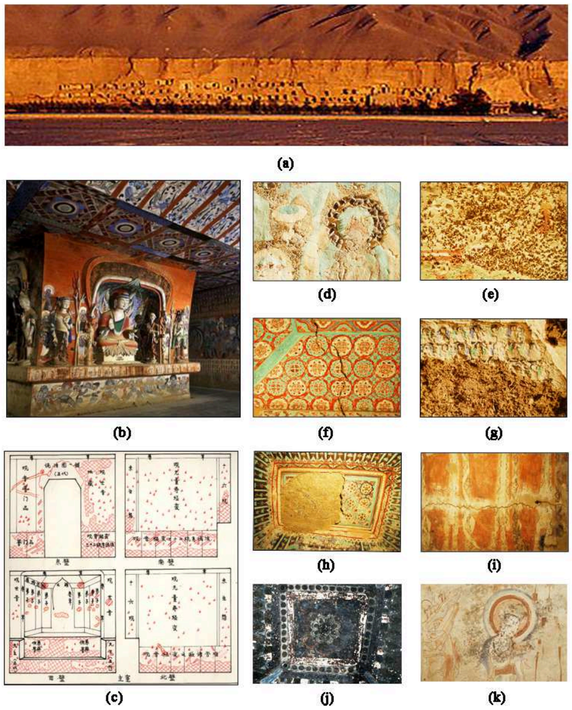


Fig. 2. Dunhuang Mogao Grottoes and the Typical Degradation Images. (a) A panorama image of the Mogao Grottoes; (b) A typical indoor scene of cave 428, North Zhou Dynasty(557-581 A.D.); (c) Graphic drawings to record the wall painting degradation in one cave, a typical used method in cultural heritage domain, and (d)-(k) Various wall painting degradation images, including flaking, blister, cracks, disruption, eruption, detachment, sootiness, and mold, in order.

## 2 Related Work

We review previous studies which are most related to ours in three categories. First, we review related techniques in high-dimensional and multivariate visualization. Second, we review related applications in cultural heritage data visualization. And third, a further research topic on cultural heritage degradation analysis, close to ours technique is surveyed.

### 2.1 High-Dimensional and Multivariate Data Visualization

In the last decade, a significant progress has been made in the visualization and visual analysis of the high-dimensional and multivariate data. Based on the graceful theory support, graph drawing, especially the clustered graph drawing methods dominated the field of hierarchical data visualization. Herman [21] and Schulz [40] have done excellent surveys on graph visualization, hierarchy visualization, navigation techniques, as well as their applications.

Parallel Coordinates visualization is one of the most popular high-dimensional techniques that was initially proposed by Inselberg [26, 27]. It is the most intuitive and widely used visualization method for high dimensional data sets.

Keim [30] designed a pixel bar charts method which is a generalization of traditional bar charts and x-y plots. To study and discover the correlations among the high-dimensional data sets, matrix-based visualization was developed. Chen [7] reviewed the history of matrix visualization [15, 18]. The use of Glyphs [44] is a common solution for visual representation of high-dimensional data sets which is also applied in our research.

Dating to 19th century, radial visualization was one of the oldest visualization methods in the statistical graphics literature. However, it is a very efficient method that is also used in our solution. Recently Holten [22] developed edge bundling algorithm for its radial layout. Radar visualization is another commonly used high-dimensional data visualization methods, which is an ancestor of radial visualization [16]. In 2008, Sharko [41] proposed a new method called Vectorised RadViz, which is formed by splitting each dimension into multiple dimensions to create a binary representation of each data record. In such case, each cluster set is separated into multiple dimensions, where each dimension represents a cluster in each cluster set. In our research paper, we also used Radar visualization and edge bundling algorithm to visualize degradation patterns. In 2009, Draper [13] made a full survey on the radial visualization techniques.

On the temporal data visualization, Havre, etc [20] proposed the famous ThemeRiver method for visualizing thematic variations over times which is now widely used in the time-varying data analysis. Dudzic, etc [14] proposed the use of coordinated views to study the temporal relationships of the data sets. Weiwei, etc [9] proposed TextFlow to understand the evolving topics of text data sets. Andrienko [4] surveyed and discussed the exploratory analysis of spatial and temporal data in details.

### 2.2 Cultural Heritage Data Visualization

Shape syntax based methods [34] have been widely used especially in the visualization of architectural heritages. Illustrations are generated by manual drawings on papers in early days to CAD based drawings nowadays [3]. For example, Huang [23] uses shape grammar to study the culture heritages.

Some great research works have been achieved in the development of capture, storage, analysis, and visualization of cultural heritage information. GIS is a useful method that is widely used in cultural heritage applications with reference to geographic location information, although it is not specifically designed for cultural heritages. In 2006, Petrescu did a survey on the status of the use of GIS technology in cultural heritage [35]. Blaise, etc in 2008 [5] proposed a framework termed informative modeling, and he also discussed the relationship between architectural modeling and information visualization. Huisman in 2009 [24] also proposed a geovisual analytic tool to support the archaeologists investigating archaeological events. Deufemia [11] in 2012 presented the Indiana Finder, a visual analytics tool for archaeologists to examine large repositories and drawings. The aim is to support the archaeologists to interpret new archaeological findings, and detect interpretation anomalies on rock carving reliefs. In 2012, Ma [32] proposed the Living Liquid, a visualization tool allowing the museum visitors to explore global phytoplankton distributions across time.

However, these studies are not in the context of conservations, and their concerns are very different compared to archaeologists.

### 2.3 Cultural Heritage Degradation Study

In the study of cultural heritage degradations, many previous works have been done and most of them were focusing on the detection of damage and deterioration. The researchers attempted to find out the causes of damages and deteriorations, such as microbiological factors [17], air pollution effects and impacts [10], hydrogeological factors [36], and environments factors [43]. As an important attempt, Chen [8] and Dorsey [12] applied photorealistic computer graphics techniques to simulate the weathering of stones and metals. However, their research aims are limited to the realistic rendering of the weathering phenomena. Late 2008, Inkpen [25] studied stone degradation. His group integrated database with GIS, and developed a simple degradation classification system. The system can be used to map the historic changes in weathering forms. In 2003, Salonia [38] developed an ARKIS system for the producing, organization, representation and utilization of knowledge of data for the recovery of historical buildings. Recently, Stefani [42] developed a web-based documentation toolkit for the visualization of stone degradation. De La Fuente [10] used GIS to present the air pollution effects on the Madrid cultural heritages in a city scale. Different visual maps have been developed to visualize the corrosion risk for the cultural heritage due to pollution. The similar GIS based method is also proposed in [29]. This type of studies is essential and important in the field. They provided fundamental understanding of particular deterioration causes, or as complementary methods of examination and analysis.

The most related idea was found in [31] which used multidimensional data visualization to study the decay of Roman Theatre in the city of Aosta(Italy). Super-quadrics glyphs are used to iconically visualize the temperature, relative humidity and contact temperature in the theatre. In addition, using flower metaphor, four concentrations and three climatic parameters are encoded as flower glyphs. However, the authors did not discuss on how the techniques were applied in the analysis of the cultural heritage decay, and they did not discuss the spatial and temporal decay patterns.

In the area of ancient wall painting conservation, many studies have been done that include the study of conservation strategies, the study of wall painting monitoring and tracking, survey and documentation and degradation causes. In 1999, Anastasiou [3] introduced the common-used documentation method for wall paintings study [1]. In the same year, Murariu [33] proposed several survey methods for the wall painting conservation. Many papers were published for the documentation of wall painting degradation [39]. These methods are mostly based on shape syntax methods with the aid of generic GIS and CAD software. Some international joint research projects and cooperations have been carried out for the conservation of grotto sites and wall paintings. In these projects, various related topics were studied. Detailed information about these projects can be found in Agnew [1, 2, 6].

In summary, although in the past, several related studies and research projects have been conducted on the data analysis of cultural heritages, there are only few efforts devoted to the customized design of visual analytics techniques and tools for supporting cultural heritage domains, especially on the supporting tools for the study of the ancient wall painting degradations which is the main motivation of our work.

## 3 Our Method

### 3.1 Multi-scale Grotto Fresco Degradation Visual Analytics Framework Overview

Our Vis4Heritage framework is shown in Fig.3. The framework is designed based on the traditional hypothesis testing methodology of cultural heritage conservations and restorations. It integrates a customary work-flow with an iterative observation-hypothesis-investigation process.

The Vis4heritage framework consists of three phases: observation phase, hypothesis phase and investigation phase. We focus on the data collected from the observation phase. These data include the survey data, caves tracking documents, images, photos and expert's knowledge. The data sets are huge and are organized in high dimensional, multivariate, and heterogeneous forms. In practice, we cleaned the data in a semi-automatic way. First we developed a data cleaning software to automatically transform the unstructured data into structured data, and then store them into databases. After that we organized students to verify the records of preliminary results one by one. When the people verify the record, each attribute is double-checked to keep consistency while the degradation severity levels are quantified at the same time. Under this process, the data sets are transformed into structured and quantitative formats that are satisfied for further analysis. Furthermore, hypotheses are raised based on the study of data and expert experiences.

To verify the hypotheses raised from the observation phase, we studied the problems we met in the investigation phase. We were considering several aspects: such as site-level degradation analysis, single cave degradation analysis, correlation and association between caves, and the temporal evolution of degradations.

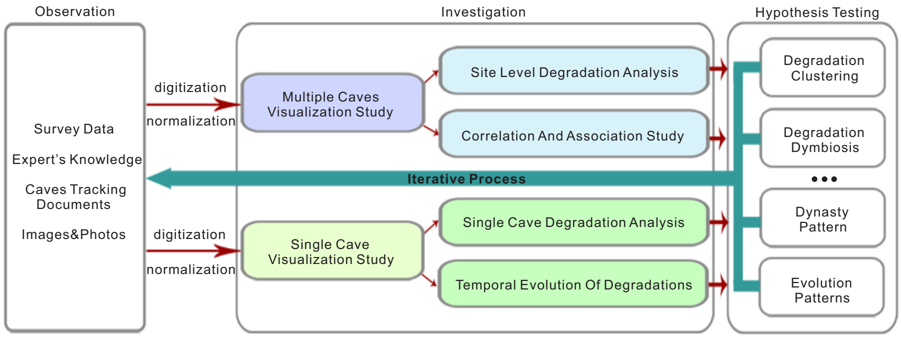


Fig. 3. The Proposed Multi-Scale Grotto Fresco Degradation Analytics Framework. An iterative hypothesis testing approach integrating an observation-hypothesis-investigation process is demonstrated.

We provide multiple views and tools to support the understanding of these analytic processes. Firstly, we designed the radial layout plus bar charts visualization tool to show the raw data that supports the site scale analysis (Section 3.2.1). Secondly, since it is essential to investigate the similarities and differences between caves, we apply domain principles in the design of tools to explore the correlations and associations between caves(Section 3.2.2). We attempted to make the implicit association between causes and degradations more clear that could help the domain experts understand and gain insights on the degradation features and patterns. Thirdly, to preserve and respect existing degradation illustration and drawing methods that are currently used by domain experts, we implement a semi-automatic image segmentation tool and present the detailed degradation severity in the form of glyphs. This tool can not only provide domain experts with a familiar degradation presentation and recording approach, which makes the data easy to understand, but also accelerate the data processing speed and greatly enhances the efficiency (Section 3.3).

Regular investigations have been strictly executed for decades in many cultural heritage sites, and the applying of digital and information techniques has over 10 year history. These collected tracking degradation data are extremely useful. To make full utilization of these data and provide enough data support for hypothesis testings, we design a temporal data visualization tool based on scatterplot and ThemeRiver techniques to present the deterioration patterns based on the wall painting survey and tracking data to gain insight into the evolution of the degradations(Section 3.4). There are some overlaps among these approaches and tools, because mutual corroboration is necessary due to the complexity of the data.

The hypothesis testing methodology in the proposed framework works in an iterative process. In this process, the verified hypothesis and conclusions can sustainably improve the process of observation and investigation, vice versa.

### 3.2 Site-level Visualization and Analysis

We believe that the full awareness, investigation, and understanding of the overall heritage degradation distribution and patterns are extremely important.

However, the traditional analytic methods are mostly for single degradation phenomenon and on restricted levels such as degradation area, the degraded wall or a single cave. Therefore, it is necessary to design a site-level analytic tool which can be used to study all the caves as a whole , providing users with common and general information about degradation phenomenon. By using this tool, users should be able to quickly gain an overview of the spatial degradation distribution. In fact, there are many caves at a grotto site, and the caves suffer from different degradations. Though different grotto sites have different degradation situations, there is only one commonly recognized degradation specification or glossary (Fig.2).

In Fig.1(c), a macroscopic view of points, an illustrated profile or panorama image is shown, which is a straightforward approach to present the overall situation of caves, however, it is too narrow and too long, and it is not scalable. In addition, due to the complexity of the degradation distribution and the degradation severity, it would be hard to find out any useful pattern in this profile. To clearly show the trend of the degradations on macro-scale, aggregated curves are used in our work as a conceptual tool, as shown in Fig.4.

We classify the caves into 3 floors, the caves near the ground belong to the bottom floor, the caves near cliff top as the top floor, and the caves between top and bottom floor as the middle floor. We use line charts method to represent the aggregated severity of the local caves. The degradations of the underlying caves are weighted to indicate the degradations in the same areas, by normalizing all the corresponding data. The different colors represent different geographical location of the caves, such as the bottom, the top and the middle floors.

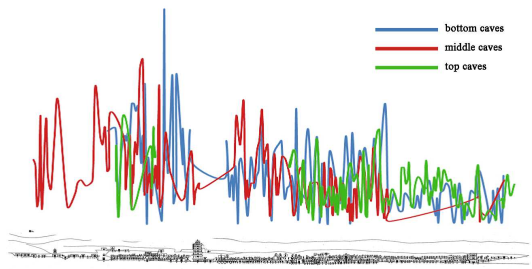


Fig. 4. An Aggregated Degradation Line Charts Tool for the Visualization of Spatial Clustering Patterns.

#### 3.2.1 Radial Layout Plus Bar Charts Visualization

To be able to visualize the global situation of caves and discover the overall site-level degradation patterns for finding detailed and accurate resolutions in the degradation analysis, we need to design another scalable site-level visualization tool. Because that the wall painting degradations are often related to the fabric of cliffs behind and the architectural structures of caves, the cave's relative position should be considered. To simulate the panorama effect, we have chosen a 3-layered radial layout design, which retains the relative cave position.

In our visualization design, three floors are mapped into three concentric rings with different radiuses respectively (see Fig.5(a)). The innermost ring represents the top floor and the outermost ring represents the bottom floor. Each ring contains several sectors. Each sector contains several caves along the radius, and the inner sector and outer sector are one-to-one mapping spatially. Caves from south to north are arranged from 0 degree to 360 degrees. Under this scheme, each cave keeps its original position linked with all others. Another important reason for using a polar coordinate plots is to increase the screen utilization ratio.

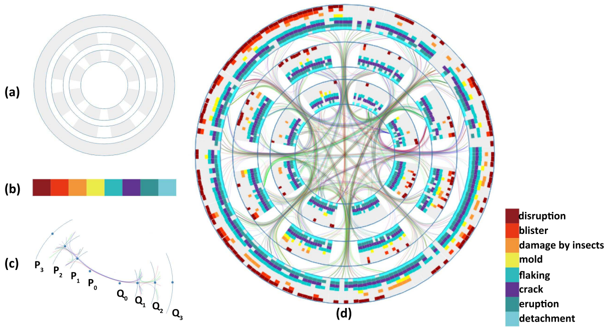


Fig. 5. Site-level analysis with radial layout plus bar charts visualization (a) 3 floors of Dunhuang Mogao Grottoes encoded by a 3-layered radial layout (b) A cave encoded by a bar charts (c) Correlation between caves encoded by links using bundle algorithm; (d) Visualization combined with a, b and c

A limitation of this solution is that the radial layout is disturbed from the view distortion due to different area covered by the inner and outer rings. We used multiple views to mitigate the perception issue resulted from distortion. We designed multiple visualization methods which will be described later, to supplement this problem especially when the user does comparison tasks. In addition, by improved interaction designs including zooming, focus+context techniques, we try our best to minimize the negative effects of distortion.

It is necessary to encode the cave-level information into the radial layout. Because of the large number of caves in each floor, the screen space allocated for each cave is limited in our visualization design. Moreover, the feature vector of this cave is formed by the multi-dimensional degradation data. To visualize these high dimensional feature vectors, we provide two visualization modes. One is a stack method where bar charts are split into several parts equally, with each part presenting one wall painting degradation type and filled with different colors (see Fig.5(b)). The other is a color blend mode where the sector is filled by different colors. The sector color is determined by mapping of the cave's feature vector (see Fig.11 (b)).

Due to the large number of data items and their complicated correlations between multi-layer caves, a straightforward visual encoding method of correlations is added for the adjacency edges between correlated caves. However, this design leads to a problem that the links are in chaos, and the inner caves may be covered. To solve this problem, we bundle the links to the control points using a similar bundle algorithm [22]. The main differences are the rules to set the control points. This algorithm is implemented and applied into the radial layout. Meanwhile, the edge bundles technique is used to reduce visual clusters and make the links more clear to see the tendency in the relations. Here we use a user adjustable threshold to avoid clutter. To reduce confusion and prevent caves from being covered by links, gaps between rings and spaces between sectors are essential. In addition, layered control points are inserted at the spaces, to bundle the links in different sectors and rings (Fig.5(c)).

Two heuristic rules are used to optimize the edge bundle algorithm. First, the outer control points are affiliated to the nearest inner space points, and the outer caves are affiliated to the nearest inner space points. Second, the links are bundled to their control points iteratively. For example, the control point of $P_{n+1}$ is $P_n$, the control point of $Q_{n+1}$ is $Q_n$, respectively, and the control points of the links are from $P_0$ to $P_3$ and $Q_0$ to $Q_3$, as shown in Fig.5(c).

#### 3.2.2 Correlation Analysis

Most of the domain experts classify the degradations into two categories: one is stable and the other is active. The stable degradations are due to particular well-studied factors and intervention measures can mitigate their deterioration, while active degradations are due to unknown factors and their changes are generally more severe.

Since the active degradations are more obvious, our correlation started with active degradations. Due to the dimension curse, we are unable to determine the correlations between caves only through the calculation of distances of the high-dimensional feature vectors. Hence, we need to use dimension reduction method, Principal Component Analysis(PCA) [28], to analyze the high-dimensional degradation feature vector data. In addition, we use a hierarchical clustering algorithm which is very similar to Ward's method [45] in our clustering study. Through these studies, we realize that there is a certain correlation degree regarding to the degradation types and severity levels, although different caves have their different geographical locations and construction periods. It has been proved that the flaking is associated with the paint loss degradations, the detachment with cracks, and the disruption with cracks.

We have found that the caves have stronger correlation if they are in the same degradation cluster. The similarity between two caves can be calculated based on the domain knowledges and clustering result. The degradation dimensions are correlated rather than independent. After PCA and clustering, we got a new feature vector $V$, representing a single cave's degradations, where $V_i$ is the $i$th degradation severity. Because we have reduced feature vectors from high dimension to low dimension, the correlation, $\tau$ is computed using:

$$\tau = \frac{1}{1+\|V_i - V_j\|} \tag{1}$$

The degradation similarity $S$ can be calculated by using the cosine similarity algorithm,

$$S = \frac{\tau_i \cdot \tau_j}{\|\tau_i\|^2 \|\tau_j\|^2} \tag{2}$$

where $\tau_i$ and $\tau_j$ are correlations of the cave $i$ and cave $j$.

### 3.3 Cave-Level and Wall-Level Degradation Analysis with Radar Map and Glyphs based Visualization

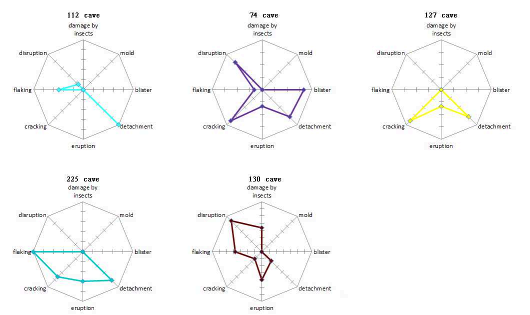


Fig. 6. Radar Maps are Used to Visualize the High-dimensional Degradation Feature Vectors Demonstrating Different Patterns.

It is necessary to develop tools, supporting the visualization of the detailed degradation information of cave, wall and particular degraded area scales for the domain experts. We utilized the Radar maps: a commonly used method in high-dimensional data visualization for visualizing cave-level degradations. The degradation data are then normalized and scaled from 0.0 to 1.0. The domain experts can analyze and compare caves based on one or more Radar maps.

Space syntax method has been widely used by the domain experts to record and study the wall-level degradations. Graphic illustrations in orthographic views are drawn by using different symbols representing different degradations, as shown in Fig.2(c). This method is fundamental and necessary for the further analysis, protection planning and tracking. Drawing the illustrations manually is time consuming, even with the help of CAD or GIS. On the other hand, the current drawing method is inaccurate for lacking of particular tools, and cannot be used for quantitative analysis.

We designed a new tool based on the idea behind by respecting this existing method as good practices. A semi-automatic tool is implemented to complete the graphic representations with orthographic views, where the symbols used are as same as those used by domain experts in the traditional recording work, as shown in Fig.7. We used different colors of symbols to represent different kinds of degradations. Users can select a particular area in orthographic view and then the tool will automatically fill the consistent symbols within the selected area. The experts can, of course, manually adjust and modify them. The proposed tool can also be combined with image segmentation technology to automatically symbolize the degradations. This combination could achieve better accuracy, uniformity, and convenience in analysis procedure. Meanwhile, another natural advantage is that the experts are most familiar with this tool, thus the experts can make full use of their practice experiences. The users can interact

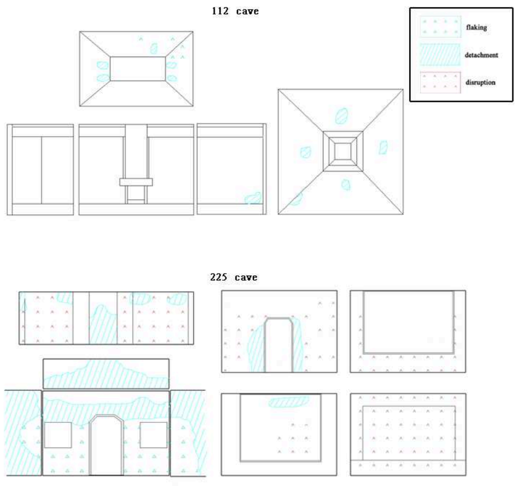


Fig. 7. The Glyph and Shape Syntax based Degradation Tools. Graphic illustrations presenting the different degradations are generated for two caves.

with the system from different views for doing their analysis tasks that towards the different resolutions for different purposes.

### 3.4 Temporal Data Visualization and Analysis

As the time goes by, the changes of degradations tend to show several evolution patterns. Experts have the certain cognition that one sort of degradation decreases while another increases. For example, blister may change into flaking, and flaking may change into eruption. These degradations are mainly caused by the humidity and soluble salt in the plaster layer and wall rock. When moisture migrates, hydration ion exchange and recrystallization will take place. Thereby it results in a blister-flaking-eruption evolution pattern. However, these empirical associations of degradations are highly related with temporal trends. It is difficult to investigate the change of degradations after a long-term monitoring. On the one hand, the evolution is a slow process, and it is difficult to track. On the other hand, it is even harder to discover evolution patterns, or to verify the hypotheses. Therefore, we need temporal visualization tools to facilitate the tracking change processes conducted by experts, discover evolution patterns of single or multiple degradations.

We designed two temporal data visualization tools that can be used to discover and verify evolution phenomena in multiple resolutions. On site scale, we use scatterplots, a common-used visualization approach, to represent the survey data (Fig.8 and Fig.9), where, horizontal axis represents the caves and vertical axis represents the survey time. We filled the node with deeper colors when the damage or deterioration is worsen, vice versa. Different deteriorations are distinguished by different shapes (or glyphs) and colors. Under this scheme, a temporal evolution view of deteriorations is generated. When a group or all caves are selected, the scatterplots visualization will show the increase and decrease of degradations over time, that clearly show the evolution patterns.

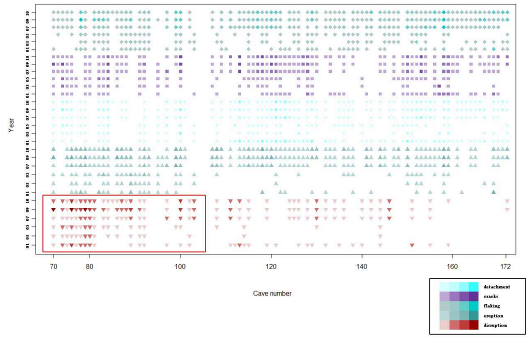


Fig. 8. The Glyph based Scatterplot Tool. The glyph based scatterplots with same degradation are arranged together.

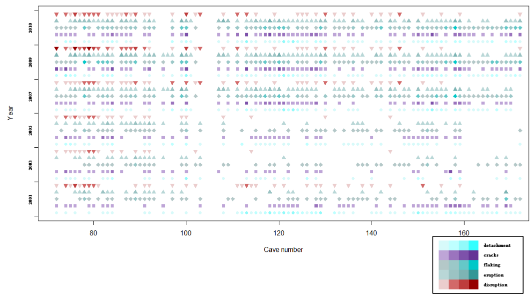


Fig. 9. Another Glyph based Scatterplots. The glyph based scatterplots with same year are arranged together.

Scatterplot visualization is a good solution when we use it to present large samples. Single cave deteriorations are also essential for experts, managers and decision makers as they often focus on a specific cave, wall, or even degraded area on a wall. ThemeRiver method is used to describe the detailed process of deteriorations on all of the three scales, as shown in Fig.13. Where horizontal axis represents the survey time, and colour mapping of the degradations is the same way as used in the scatterplots. Wider river means the corresponding deterioration becomes worse, vice versa. Scatterplot and ThemeRiver tools can show different detailed information depending on different experts' perspectives. The use of a variety of visual tools makes our framework robust and exhaustive.

### 3.5 Interaction Design

For the investigation of degradation, visual interactions are as important as visualization itself. Interaction design is not only necessary for a single tool design, but also essential as a part of the framework that is for many different tools. Common visual interaction techniques, including fisheye view, zooming and filtering, are adopted in our solutions. Overview+detail and focus+context are also designed to coordinate multiple views.

In the radial layout plus bar charts visualization technique, we use the fisheye interface to check caves more precisely, which is another effort to reduce distortion of the radial layout. Information in the panorama maps is easier to be found using zooming interface. Zooming function is also provided in the glyph and shape syntax based degradation analysis tool, and it is especially useful when browsing on the wall and degraded area level in a cave. We provide visual interface to filter caves in the site-level tools by degradation and dynasty. As a highlight, we specifically designed a dynasty filtering tool. It is represented by ellipses which are arranged on an axis, in which principle axes represent the dynasty duration and the caves constructed in that dynasty.

Focus+context view is widely applied in our tool design. Taking the single tool design as example, when we highlight one or several caves using fisheye, the overall site profile or radial layout becomes the context to keep the relative location hints. Another example is when we focus on a particular degraded area or wall, in the glyph and shape syntax based view, cave-level illustration acts as the context. Focus+context view is also designed as a main interaction and navigation method between multiple views. When a user focuses on a relative detailed scale, relatively macro-scale views become context. For instance, when users select caves in the line charts or radial layout, Radar maps simultaneously present the detailed and focused information of the caves.

All the tools used in our project are synchronized, and experts can choose whichever tool they like to start the investigation task. Some functions of these tools may be overlapped, and enhanced by each other. A particular investigation task can be accomplished by using a combination of tools under our framework, with customized task requirements.

## 4 Evaluation

We evaluate our work through case studies and expert's review methods.

### 4.1 Case Studies

#### 4.1.1 Dunhuang Mogao Grottoes and the Degradation Data

As a national priority project, we conducted our research in Dunhuang Mogao Grottoes, a UNESCO declared World Heritage site on the Silk Road, located near the ancient town of Dunhuang in Gansu Province, located in the northwestern of China. In Dunhuang, 735 well-designed caves are excavated in the steep rock cliffs of soft conglomerate along 2.5 kilometers long riverside in a Gobi desert surroundings. Totally in this ancient Buddhist site there are more than 45,000 square meters of wall paintings and 2,000 statues in 492 caves that were excavated dating from the fourth(starting from 366 A.D.) to the fourteenth centuries comprising the largest body of Buddhist art in China.

For so many centuries, these paintings had suffered from various kinds of deterioration, including the flaking of the paint layer and the progressive loss of adhesion between the conglomerate and the clay plaster. Among various efforts, field surveys have been implemented and regarded as regular tasks in the Dunhuang Academy in the ways from the manual and paperwork forms in early days, to the monitoring and acquisitions of the wall painting and degradation status information in the digital formats nowadays. The degradation studies have also been carried out by different domain experts and via international collaborative projects.

The survey data collected by Dunhuang Academy are in two categories: text data and image data. The text data contains textual documentation recording degradation status of 492 caves dated from 2001 to 2010. These are unstructured data with redundancies. The textual documentation contains information about the cave number, the recording date and time, the cave structure in graphic formats, the degradation position, degradation categories, and descriptions in more details. The image data, on the other hand, contains lots of glyph based hand drawings and photograph images of degradations. These image data revealed a certain degree of the degradations severity and distribution on the wall, but they cannot be directly used for information retrieval and analysis. As domain experts have their own domain-specific requirements, these data cannot be directly used.

It is easy to extract cave, wall information from the above data sets. However, it is relatively hard to extract degradation category and severity degree information from the above survey documents, as originally these data are only in text descriptions. Degradation severity can only be obtained from text description and image data manually. This is our initial motivation of the projects. By using our proposed semi-automatic data cleaning software, 10 students are required to extract the degradation category, and quantify the severity level from the descriptions. The results are cross-checked at least twice.

We have also consulted with the domain experts to confirm the reliability of our normalized and digitized data. Finally two datasets are obtained. The first dataset containing 7,758 records is describing the current situation of Dunhuang Mogao Grottoes. Each record contains the cave number, construction dynasty, degradation categories, spatial location and degradation severity. The second data sets containing 27,885 records of the 10 years of temporal degradation data. Each record contains the cave number, survey year and severity of degradations. With the obtaining of these data, we would make the following hypothesis:

1) Caves have explicit similarity of deterioration categories and severities if they are spatially close to each other.

2) Different kinds of degradations may always occur at the some caves and even in the specific area on the wall.

3) If caves were constructed in the same period, they must have something in common, such as their locations or degradation patterns.

4) There might have some facts for verifying the evolution patterns.

#### 4.1.2 Case Study 1: Spatial Degradation Clustering

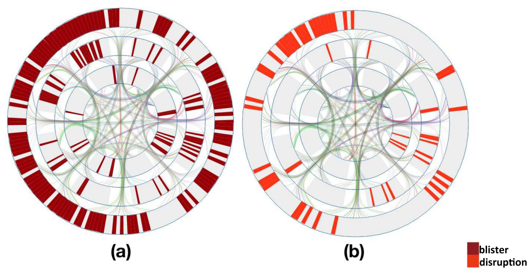


Fig. 10. Spatial Degradation Clustering. (a) Disruption are mostly located on the bottom floor of Dunhuang Mogao Grottoes; (b) Blister are mostly located on part of the bottom floor of Dunhuang Mogao Grottoes.

When data sets are classified by categories, some types of degradations are presented in a very equal distribution patterns. The radial visualization is a typical example of such case. We select a single degradation and check its distribution pattern. Types 2 of 8 of degradations show a sound clustering. In Fig.10(a), red bars representing disruption are mostly located on the outer ring of the radial layout. Moreover, in Fig.10(b), orange bars representing blister are mostly located on the outer ring. It seems that there is a reasonably high correlation between two types of degradations and the ground, as the outer ring stands for the bottom floor.

To verify our hypothesis, firstly we use the aforementioned orthographic views (Fig.7) to check the detailed situation of the degraded caves. Disrupted and blasted areas are mainly located on the lower position of the wall (which means they are closer to the ground). Then we check the source survey data and made a simple statistics. The results show that around 78% of all the caves with disruption are located on the first and second floors, while 83% of the caves with blister are located on the first floor and right side of the cliff, this investigation result is consistent with our visualization outcomes. Source survey data also show that the severity of caves located in the lower are commonly higher than those located in the upper location.

So the question is that why these two degradations can show such an obvious principle while others would not? We then communicated with Dunhuang Academics about our discoveries. They verified our hypothesis and gave us an explanation, that is the blister and disruption are caused by soluble salts and the change of moisture. The closer the caves to the ground, more moisture there is. It means that there are more chances to cause these two kinds of degradations. Specifically, the right side of Mogao Grottoes is much lower than the left side, which can be seen in the panoramic view in our framework (Fig.1(c)). It clearly illustrates the distribution pattern of blister. Our discoveries reflect this discipline. On the other hand, other types of degradations do not have such direct association with moisture. Therefore, they show no spatial clustering pattern.

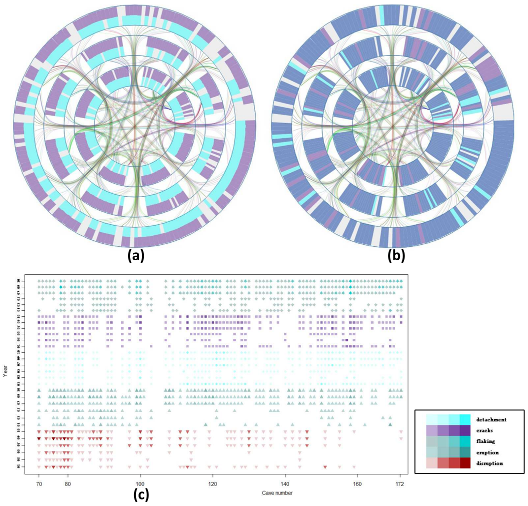


Fig. 11. Degradation Symbiosis Discovery in Three Ways. (a) Stack method; (b) Blend method; (c) Scatterplots.

#### 4.1.3 Case Study 2: Degradation Symbiosis

In case study 1, we have analysed a single degradation case with the use of the radial visualization tool. In this section, we will analyze the associations between two degradations. We have found that when we choose all the degradations(see Fig.1(a)), inner rings of the bar charts with cool colored will appear in almost every cave. Therefore we choose two of them and study their distributions on scales ranging from the site to area on the wall.

On the site scale, as shown in Fig.11(a), we found that most of caves have degradation crack and detachment. We choose the color blending mode to check and see if these two kinds of degradations have coexistence patterns. The result is shown in Fig.11(b), in which purple and light blue bars represent crack and detachment respectively. A dark-blue Mixed color represents the coexistence, and account for the majority. We can see that the coexistence as shown in Fig.11. Statistics show that 87% of the caves have crack deterioration, 85% have detachment, and 82% of the degraded caves have both of these deteriorations. Hence, it is believed that these two degradations are symbiosis.

To verify our assumption, we further analysed these two degradation cases using cave-scale method with other tools. We selected caves and see the Radar maps (see Fig.6) of them. In most cases, around 76%, the aforementioned two degradations present a positive correlation pattern. In the orthographic views (Fig.7), in which we have different resolutions of a wall and area on the wall, glyphs representing crack and detachment coexist and their positions are close to each other and even overlapping. This is another proof of our assumption.

Dunhuang Academics provided their understandings on the phenomenon. In fact, both of crack and detachment are associated to the cliff fabric. When plaster layer detaches from cliff, detachment occurs followed by crack. Our discoveries are beyond the experts' expectation, as we are of little awareness of the degradation mechanism.

#### 4.1.4 Case Study 3: Degradation Pattern with Construction Dynasty

There are 492 caves in Dunhuang Mogao Grottoes that were constructed over a long period. We can select a specific dynasty to visualize their distributions and degradations. Fig.12(a) shows a radial visualization of caves that are constructed in Northern Liang Dynasty. In this era, 8 caves were constructed, 7 of them were constructed on the second floor and 1 was on the third floor. Their deteriorations are mostly stable categories including crack, detachment, flacking and eruption. There are 90 caves constructed in Sui Dynasty(as shown in Fig.12(b)), most of them are located on the second and third floor, and they have almost the same features with those 8 caves constructed in Northern Liang Dynasty. During Sheng Tang Dynasty, 96 caves were built. It is the Dynasty that built the largest number of caves in comparison with other dynasties(see Fig.12(c)).

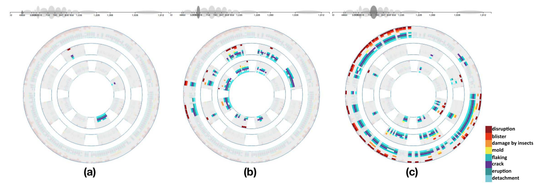


Fig. 12. Degradation Pattern with Construction Dynasty. (a) Degradation situation of Northern Liang Dynasty; (b) Degradation situation of Sui Dynasty; (c) Degradation situation of Sheng Tang Dynasty.

As most caves were built in Sui and Sheng Tang Dynasties, we focused our analysis of degradation pattern and sample collection in these two dynasties. Fig.12(b) shows that only 5 out of 90 caves are located on the bottom floor, while the rest are located on the middle and top floor. On the first floor, disruptions are occured in 4 out of 5 caves(80%); on the middle floor, disruptions are occured in 9 out of 64 caves(14%); and on the bottom floor the number is 4 out of 21(19%). And in Fig.12(c), on the bottom floor, disruptions are occured in 47 out of 62 caves(75.8%); on the middle floor 3 out of 24 (12.5%), and 4 out of 10 (40%) on the top floor. With these statistics, we found that disruption on the bottom floor has the highest frequency of occurrence(80%) in Sui and 75.8% in Sheng Tang Dynasty, then followed by the top floor, and lowest frequency of occurrence is in the middle floor (14% and 12.5%). This is also related to moisture, as bottom floor is close to the ground and upper floor is affected by the rain.

Dunhuang Academics confirmed our findings, they showed us by using our tools that the early dynasty caves are mainly located on the middle floor. Up to Sui Dynasty, most caves were constructed on the middle floor because of the superior geographical environment. In Tang Dynasty, due to space constrains, caves had to be built on the bottom and top floors.

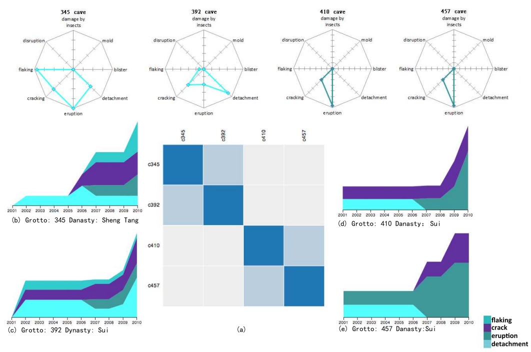


Fig. 13. Degradation Pattern Discovered while Tracking the Annual Survey. (a) Correlation between caves; (b) Degradation tracking of cave 345; (c) Degradation tracking of cave 392; (d) Degradation tracking of cave 410; (e) Degradation tracking of cave 457.

#### 4.1.5 Case Study 4: Degradation Pattern Discovered while Tracking the Annual Survey Data

In this case study we tracked the annual survey to find out changes of degradations during the past decade. To analyse the temporal data, we first used scatterplot visualization to illustrate the change of degradation severity on site scale(see Fig.8 and Fig.9). The highlighted area in Fig.8 shows an apparent deterioration trend, in which disruption are represented as red triangles while their colors fading out to dark over time. When we select one or more caves and explore the cave information, the ThemeRiver visualization tool will show us the intuitive figures about the increase and decrease of all kinds of degradations during the past 10 years. As shown in Fig.13, the light blue stream decreases when the green stream increases, and he purple stream also increases. This track visually describes the process of the transformations from one degradation to others(in our case, it changed from detachment to crack and eruption).

The Matrix visualization shows that cave 345 and cave 392 have a high similarity while cave 410 and cave 457 are even more similar. However, these two pairs are not similar to each other. The difference is that because of the flake, we can hardly, if any, capture the difference between different year's image data, unless over a long period.

We checked the tracking reports of some specific caves, and consulted with Dunhuang Academics. The tracking reports have shown a clear evolution pattern which can hardly be noticed by curators because their associations are so implicit. With decades of experience, some experts told us that they had noticed some signs that there may be, if any, evolution patterns. However, they admitted that without our tools, these patterns could never be so clearly confirmed.

### 4.2 Expert Review

22 experts from Dunhuang Academy participated in our evaluation. These experts are from different departments acrossing multiple disciplines, including microenvironment researchers, archivists, geologists, chemists, conservators, restorers, curators and so on.

They are professionals in different fields relating to degradations of Dunhuang wall paintings and they will verify the existing knowledges or some hypotheses by operating the tools personally. After getting familiar with the tools, they are asked to finish our questionnaire which are in seven categories: aesthetic, visual design, interaction, learnability, performance, functionality, and knowledge discovery. Meanwhile, in order to acquire more feedbacks on applying these tools in the Dunhuang wall painting degradation study, we then start to discuss openly and focus on some specific problems with these domain experts. To quantify the used time, we record the time that each expert spend to find out or confirm a particular answer, which is informed in advance. The average used time spent to confirm an answer is 45secs. The statistical results includes the lowest score, the highest score, average score and variance, are shown in table 1 and the Fig.14.

Table 1. Expert Review Results. The Full Score for Each Factor is 10

| Factor | Highest | Lowest | Average | Variance |
|---|---|---|---|---|
| Aesthetic | 10 | 8 | 8.8 | 0.51 |
| Visual Design | 9 | 7 | 8.6 | 0.53 |
| Interaction | 9 | 6 | 7.7 | 0.56 |
| Learnability | 9 | 6 | 7.8 | 0.81 |
| Performance | 8 | 6 | 7.5 | 0.55 |
| Functionality | 9 | 7 | 8.3 | 0.64 |
| Knowledge Discovery | 9 | 7 | 8.2 | 0.56 |

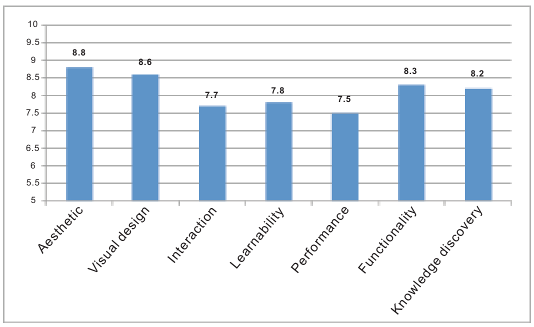


Fig. 14. Expert Review Results. This bar charts is generated based on the average scores.

From the results, we can find out that most experts give overall aesthetic and visual design a good rating. User interface looks comfortable and visual design is very suitable for the long and hierarchical structure of Dunhuang Mogao Grottoes. Most of pre-defined knowledge is found by using our tools, but some experts mention that the information cannot be read easily. So they give relatively high score in functionality comparing to knowledge discovery. They give relatively low score in interaction and learnability. They hope that the interaction design could be improved as the way they are used to be, and more hints should be provided to help their interactions. On the other hand, it may be that they have less chance to contact visualization tools and their real operating time is too short to learn. The performance score is the lowest. It is because of the large volume of data, so the response time is relatively long. The variance of learnability and functionality is relatively large. Because both their operating time and research background differ from person to person, resulting in large score differences compared to other factors.

To summarize, all of them are very interested in applying our visualization tools in their daily work. It is worth mentioning that they believe that our work is a combination of heritage conservation and visual analytics, and regard it as a significant work. They can discover information about grotto wall paintings conveniently instead of on-site investigations. Moreover, they consider it as a contribution to the heritage conservation.

## 5 Conclusion and Future Work

This paper proposed a new visual analytics approach for analyzing and visualizing the wall painting degradations. A multi-scale visual analytics framework is proposed and several hypothesis testing tools are developed for assistance of cultural heritage domain experts' work, including a radial layout plus bar charts tool for the overall visualization at site scale, an aggregated visualization tool with line charts combined with Radar maps to explore the overall and detailed degradations in various scales, a matrix visualization tool to study the correlations, and a semi-automatic glyph and space syntax based tool to support the degradation illustrations, which is not only compatible with the domain experts' working experiences, but also performs a good efficiency. A ThemeRiver based temporal investigation tool is also developed. Furthermore, several case studies have been conducted with real cultural heritage data, new discoveries are found by using hypothesis testing methods. Expert reviews are also executed to evaluate our approach.

In the future, we will collect more degradation related data using sensors, such as air pollution data, cliff stability, seismic data, microenvironmental monitoring data, and the tourists data, and further explore the underlying associations.

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