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Research article

ArtEyer: Enriching GPT-based agents with contextual data visualizations for fine art authentication

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ABSTRACT

Fine art authentication plays a significant role in protecting cultural heritage and ensuring the integrity of artworks. Traditional authentication methods require professionals to collect many reference materials and conduct detailed analyses. To ease the difficulty, we collaborate with domain experts to develop a GPT-based agent, namely ArtEyer, that offers accurate attributions, determines the origin and authorship, and executes visual analytics. Despite the convenience of the conversational user interface, novice users may still face challenges due to the hallucination issue and the steep learning curve associated with prompting. To face these obstacles, we propose a novel solution that places interactive data visualizations into the conversations. We create contextual visualizations from an external domain-dependent database to ensure data trustworthiness and allow users to provide precise instructions to the agent by interacting directly with these visualizations, thus overcoming the vagueness inherent in natural language-based prompting. We evaluate ArtEyer through an in-lab user study and demonstrate its usage with a real-world case.

1. Introduction

Art painting has been cherished by a wide range of collectors due to its significant cultural, artistic, and economic value. These immense values have also attracted numerous illicit profiteers who produce counterfeit paintings to gain unjust economic benefits. Due to a lack of expertise in distinguishing authentic paintings from counterfeit ones, most collectors can only seek authentication services from professional connoisseurs. However, the scarcity of professional connoisseurs often prevents collectors from obtaining reliable authentication services owing to the overwhelming number of paintings that need to be authenticated.

The recent advance of Generative Pretrained Transformer (GPT) has brought new opportunities for achieving easy-access painting authentication. Like other GPT-based AI agents in professional domains (Li et al., 2023), the key to successfully integrate GPT into painting authentication is imbuing GPT with the necessary knowledge and mitigating the hallucination issue, referring to the phenomenon where a model generates outputs that are plausible but incorrect or fabricated. For instance, GPT needs to grasp the characteristics of paintings by different artists across multiple dimensions, such as inscriptions, seals, and brushwork. Despite the vast number of painting images publicly available from museums and the painting characteristics summarized by connoisseurs, how to utilize this data to construct a professional and trustworthy authentication agent remains an open problem to resolve.

To enhance GPT on tasks requiring complex reasoning, a widely-used approach is chain-of-thought prompting (Wei et al., 2022; Zheng et al., 2023). Specifically, we need to guide GPT in analyzing paintings step by step from different dimensions in the fine-tuning stage. To ensure that GPT has a comprehensive understanding of the artist's paintings, an effective practice is to employ retrieval-based knowledge augmentation (Lin et al., 2023; Ye et al., 2024). For example, we need to provide GPT with relevant information from all of an artist's paintings so that GPT can determine whether the painting could be attributed to this artist. However, GPT still exhibits the hallucination issue even with such Hu et al. (2023). The existing mitigation methods typically involve offering reference indexes of GPT's answers,[1,2] enabling users to

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[1] https://copilot.microsoft.com
[2] https://app.txyz.ai

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check whether there are correct correspondences between the answers and the references. While these methods are extensible, they cannot be directly applied to painting authentication as they overlook the intensive labor users require when inspecting the paintings.

To face these challenges, we develop a novel GPT-based agent, named ArtEyer, to facilitate easy-access painting authentication. We collaborate with two professional connoisseurs to understand their general workflow and summarize three analytical dimensions for painting authentication. To improve ArtEyer's trustworthiness, we place data visualizations into conversations to illustrate underlying data facts. These meticulously designed visualizations are generated according to the statistics derived by comparing the target painting with reference paintings. Specifically, we leverage traditional computer vision techniques to complete the comparative analysis of paintings and calculate the corresponding statistics automatically. Moreover, we leverage GPT to interpret visualizations so that general users can easily understand visualization encoding. To ease the difficulty of language-based prompting, we enable users to prompt agents by interacting with contextual visualizations. Such interactions enable users to manipulate data items, which are further included in pre-defined prompts, thus enabling ArtEyer to respond directly to user interactions. Ultimately, we demonstrate the usage of ArtEyer through real practice and conduct a user study to validate its usability.

The main contributions are summarized as follows:

- We work closely with professionals to understand the workflow and design goals for artwork authentication.
- Based on that, we develop ArtEyer, a novel GPT-based agent that leverages contextual data visualizations to facilitate trustworthy and controllable human-AI conversations.
- We validate the effectiveness and usability of ArtEyer through a usage scenario and a user study.

2. Related work

This section introduces relevant studies about painting authentication and GPT-based agents.

2.1. Painting authentication

Traditional authentication is typically conducted by domain experts, involving a complex and meticulous process. Taking Chinese paintings as an example, experts consider various aspects, such as medium, content, seals, inscriptions, and other elements (Museum, 2000). They also refer to historical records to gather details like the artist's era, titles, mentor relationships, and life experiences. However, the traditional methods are time-consuming, labor-intensive, and prone to subjective biases (Guan et al., 2005). Given the prevalence of digital paintings, it has become increasingly common to leverage the capabilities of computers to address these limitations.

Computer-aided authentication of digital paintings involves extracting color, texture, shape, and other characteristic information that effectively represents the artist's unique style. Since the introduction of color histograms (Swain and Ballard, 1991), color information has played a significant role in painting authentication processes. For instance, Wang and Huang (2020) defined information richness from the perspectives of dominant colors and color complexity to detect key areas in oil paintings. Xie et al. (2022) extracted color features and used a decision-level fusion algorithm based on adaptive weights for oil painting style classification. Unlike Western paintings, which rely heavily on detailed color histograms, Chinese paintings primarily use line strokes as their main expressive form (Pflüger et al., 2019). Liu and Sheng (2017) extracted Chinese painting features based on stroke shapes and ink intensity, while Qiao et al. (2020) proposed a new stroke feature extraction method involving edge line filtering and connection.

Advanced artificial intelligence has enhanced researchers' ability to extract high-level visual features from paintings. For example, Jiang et al. (2019) combined discrete cosine transform with convolutional neural networks for the classification of Chinese painting techniques. Sheng et al. (2020) proposed a deep network feature aggregation recalibration algorithm for the emotional classification of Chinese paintings. Li and Zhang (2021) used multi-scale convolutional neural networks to capture local features of Chinese paintings for the classification task. Cai (2022) proposed a pseudo-linear directional diffusion equation to identify the most representative local areas of Chinese calligraphy and painting stroke styles. As for painting authentication, transfer learning is used to improve the identification accuracy of Raphael's works to 98% (Ugail et al., 2023).

Notice that seals and inscriptions in Chinese paintings provide additional assistance in their authentication. Due to the invariance of the same seal on different artworks, seal identification often relies on direct matching (Chen, 1995). Researchers have also improved seal-matching algorithms using methods such as circular projection template matching (Yang and Wang, 2001) and edge difference histograms (He et al., 2012). In recent years, deep learning has been applied to the extraction and recognition of seals. For example, Dun et al. (2022) proposed a Feature Pyramid Network Selector (SEL-FPN) to address the issue of limited seal datasets. As for inscriptions, being handwritten text, they can be identified using handwriting recognition methods (Sabourin et al., 1997). Many algorithms that are more suitable for inscriptions have been designed based on the characteristics of Chinese calligraphy. Zhai et al. (2020) improved deep learning models for extracting inscriptions and used a style loss function to compare different artists' styles. Zeng et al. (2022) combined the results of three neural networks using average decision fusion to extract font details more accurately. Rexit et al. (2022) proposed an Improved Discrimination Network (IDN) that enhanced the accuracy of signature authentication on Chinese handwritten signature datasets.

Although computer-aided identification methods can compensate for human limitations, they still have many shortcomings. Currently, computer-aided methods mostly train models for specific elements of works by one famous painter (such as strokes or seals), lacking comprehensiveness. For a few well-known painters with a large number of works passed down (such as Van Gogh or Shi Tao), highly accurate identification models have been developed. However, most painters' works have limited extant examples, which is insufficient to support model training. Moreover, the deep features extracted by models are non-interpretable and non-interactive (Pflüger et al., 2019), leading to a "black box" problem that undermines trust in model outputs. Therefore, when art enthusiasts are unsure about the authenticity of their collected artworks, they still prefer to consult experts. Consequently, an objective, efficient, comprehensive, and user-oriented identification method is necessary.

Recently, the rapid rise of multimodal large models has brought new opportunities to various fields. Represented by GPT-4, multimodal large models excel in text generation, text understanding, multi-turn dialogue capabilities, as well as image understanding and generation. Unlike traditional machine learning models, GPT requires only minimal training data to achieve decent results. Furthermore, conversing with a GPT-based agent has become a new form of interaction that aligns with human intuition and is easily accepted by users. Applying GPT-based agents combined with data visualization to facilitate painting authentication can

efficiently analyze various aspects of artworks based on data-driven insights. In ArtEyer, we provide GPT with professional knowledge and relevant data and use a multi-agent framework to generate visualizations and textual analyses to facilitate artwork authentication.

2.2. GPT-based agents

Recently, GPT has been widely adopted to facilitate complex analysis and reasoning. For example, Zhao et al. (2024) applies the LLM agent as the Experiential Learning agent to emphasize the importance of accumulating experience, which improves the efficiency of GPT by utilizing its capability of memory. Wei et al. (2022) and Zheng et al. (2023) leveraged chain-of-thought prompting to guide GPT analysis step by step, which avoids the constraints of GPT's memory capacity and eases the issue of hallucination. In real-world practices, Li et al. (2024) proposed EcomGPT to focus on developing E-commerce agents that divide a complicated task into atomic tasks. Hou et al. (2024) deconstructed the process of color design into a series of sequential steps interwoven with user interactions involving GPT. To make GPT more professional, training or fine-tuning LLM with domain knowledge is essential. EcomGPT is trained with EcomInstruct, and C2Ideas is trained by applying the domain knowledge of color design. Hou et al. (2024) enhanced the training process of their model, namely ChatLaw, which integrates four modules during inference: "consult", "reference", "self-suggestion", and "response". Apart from solely relying on the model itself, cooperation between human experts and GPT agents further improves the reasoning capability. VISAR (Zhang et al., 2023) embraces the concept of collaboration between a writer and a GPT agent, employing the chain-of-thought method to interactively assist the writer in exploring potential discussion points. Zhou et al. (2024) proposed a new framework in which LLM is used to implement a non-linear artificial intelligence collaboration process, allowing for more effective communication with human users.

While these methodologies undoubtedly showcase their versatility, their application in tasks such as painting authentication proves to be particularly challenging. These methods fail to consider the critical aspect of the substantial effort required from users, who must meticulously examine numerous intricate elements of a painting. For example, users attempting to authenticate a painting must grasp and retain the nuances of various features, which can pose a significant cognitive burden, especially when there is a large number of visual information to consider. Thus, it is essential to face these challenges to enhance the capabilities of GPT within the domain of painting authentication.

3. Background

To gain a deep understanding of painting authentication, we collaborated for three months with two senior connoisseurs (EA and EB) from one Chinese art authentication institution. During the collaboration, we visited the institution twice to engage in discussions with the connoisseurs. We also maintained weekly one-hour online meetings with these two connoisseurs to iterate on the design of ArtEyer. Based on the connoisseurs' experiences, we introduce three high-frequency dimensions for painting authentication and summarize a series of design goals they require when providing authentication services to collectors in this section.

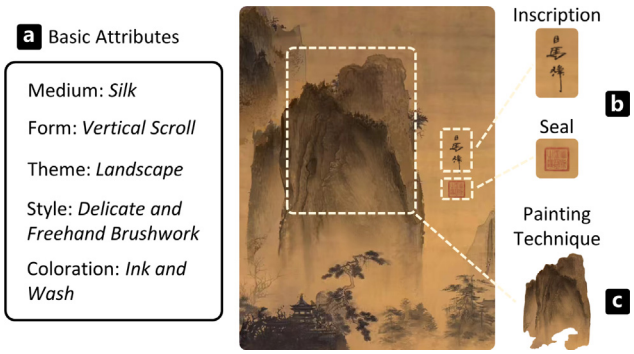

Fig. 1. Three authentication dimensions of paintings: (a) basic attributes (e.g., medium, form, theme, style, coloration), (b) inscriptions and seals, and (c) painting techniques.

3.1. Painting authentication

Painting authentication refers to determining whether the content of paintings aligns with their identities. The painting's content encompasses multiple dimensions of information, such as inscriptions, seals, and painting techniques. The painting's identity can be divided into those of authors and collectors. The dimensions typically considered for painting authentication are as follows:

Basic attributes (Fig. 1**a).** Art practitioners have built a comprehensive taxonomy to classify various traditional paintings based on their basic attributes. In the context of Chinese painting, the attributes include medium, format, theme, style, and color scheme. Considering the diverse historical backgrounds of artists, their paintings exhibit varying distributions across these attributes. A painting may be counterfeit if its basic attributes deviate significantly from the distribution of known paintings by its author. For example, EA pointed out that Keran Li, a famous painter in modern and contemporary China, never painted horizontal scroll landscape paintings. Therefore, any horizontal scroll landscape paintings with his identity are essentially counterfeit.

Inscriptions and seals (Fig. 1**b).** Inscriptions and seals are particular elements within Chinese paintings appended by their authors or collectors. They not only represent the painting's identity but also provide additional clues for connoisseurs to distinguish between authentic and counterfeit paintings. Seals are especially regarded as a critical dimension in authentication due to their inherent physical permanence. For a painting, connoisseurs will examine the seals it contains to determine if they belong to known ones used by the seal owner. Moreover, they will compare the seal's position to determine whether it conforms to the seal owner's stamping habits. For example, EB indicated that Emperor Qianlong of the Qing Dynasty in China is well-known for his penchant for stamping seals in arbitrary positions on paintings. Thus, discovering his seals at the center of a painting would be considered normal.

Painting techniques (Fig. 1**c).** The long history of Chinese art has given rise to a variety of painting techniques. For example, there are as many as sixteen different "cunfa" techniques for depicting textures of mountains, rocks, and tree bark in Chinese paintings. Except for a few master painters, most painters have techniques that they excel in or prefer. For instance, Li Cheng, a famous painter in the Song Dynasty of China, innovatively depicted the textures of rocks resembling curled clouds, birthing a technique known as "Juanyun cun". Connoisseurs will analyze the techniques involved in a painting to judge whether these techniques conform to the technical characteristics of its author.

3.2. Reference materials

To enhance GPT's ability to authenticate paintings, we collected reference materials that would be injected into GPT as extra domain knowledge. Taking Ma Yuan, a famous Chinese painter of the Song dynasty, as an example, we gathered images of his paintings, along with their basic attributes, inscriptions, and seals from museums' public data. For each painting, we manually annotated the positions of all inscriptions and seals. Furthermore, we employed an interactive segmentation tool[3] to extract the main objects depicted in the paintings and annotate each object with information such as categories and techniques employed. We also organized a dictionary of painting categories involved in basic attributes and painting techniques, with detailed textual explanations and corresponding illustrated examples accompanying each item.

3.3. Design goals

To capture collectors' genuine requirements, we gathered numerous online videos that record real cases where collectors sought painting authentication services from connoisseurs. After watching all the videos, we sorted an initial list of user requirements. Subsequently, we presented this list to the collaborated connoisseurs during an online meeting and requested them to review each requirement. We also asked them to supplement this list based on their individual experiences providing authentication services. Based on these user requirements, we distilled three design goals:

- **G1 Explaining authentication results.** Collectors may not necessarily trust all the authentication results, especially when the results conflict with their perspectives. Therefore, the system needs to provide detailed explanations of the logic behind the authentication results and offer accurate evidence to support its viewpoints.
- **G2 Clarifying professional terms.** Connoisseurs inevitably use some professional terms when explaining authentication results to collectors, which users may not understand. Thus, the system should be able to interpret these professional terms for collectors.
- **G3 Supporting the exploration of reference materials.** Collectors often express curiosity about specific data insights during the painting authentication services. Therefore, the system needs to support the proactive exploration of reference materials.

4. ArtEyer system

Based on the design goals, we developed ArtEyer, a GPT-based tool that provides collectors with easy-access painting authentication. We first provide an overview of our system, followed by the visualization methods that support the authentication of paintings from the above dimensions.

4.1. System overview

As shown in Fig. 2, Our system consists of two main components that support authentication tasks. The visualization component receives digitized paintings and issues from users and presents inferences with visualization illustrations, which facilitates the reasoning process of painting authentication in a conversational manner.

[3] https://segment-anything.com/demo

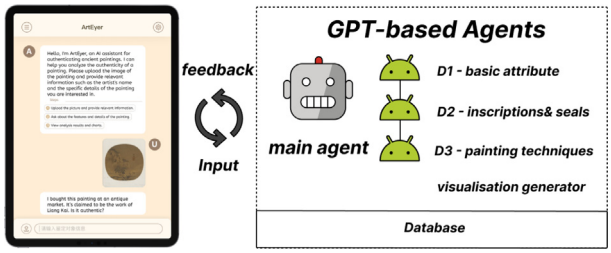

Fig. 2. ArtEyer comprises a visualization component (left), which provides a conversational reasoning process for painting authentication, and an agent component (right), which generates answers embedded with interactive visualizations.

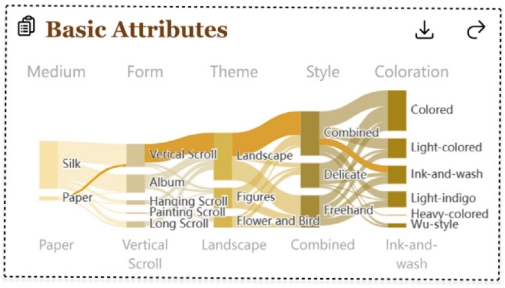

Fig. 3. The attributes of an artist's paintings are depicted through a Sankey diagram, with the given painting's attributes highlighted by a prominent flow.

Based on the user input, the agent component analyzes the professional terms and focused dimensions and derives respective detailed analysis strategies to generate the feedback (**G2**). Specifically, the agent component comprises an agent group and a database. The agent group leverages a main agent that recognizes the analysis dimensions and assigns them to respective subagents. Subsequently, the subagents leverage their only strategy to generate text feedback and utilize a visualization generator to create interactive visualizations. Finally, the main agent collects those answers and generates comprehensive feedback for the visualization component. All the agents are built upon GPT-4V to ensure the efficiency of input interpretation and feedback generation. The database stores the paintings and their metadata to support attribute statistics and searching.

4.2. Basic attributes dimension

The comprehensive overview of basic attributes is critical to understanding the artist's preferences and the level of conformity of this painting. To explain the difference between the basic attributes of a given artist and a painting (**G1**), we leverage the Sankey diagram that visualizes the distribution of each attribute and reveals multi-dimensional attributes through flow patterns. As shown in Fig. 3, each dimension is encoded by a specific color, corresponding to a basic attribute identified through the above label. The width of each cell within the dimension represents the proportion of paintings that have this attribute among all paintings. The proportion value is displayed while hovering on the corresponding cell. Thus, the cells within one dimension reveal the preference of the painter, while the wider flows represent the mainstream paintings.

To enable comparison with a given painting, we highlight the flow corresponding to its attributes and identify its attribute value with the label below each dimension. Such a method enables the identification of abnormal paintings intuitively through the thinnest part of the highlighted flow. For instance, Fig. 3 shows that the flow of the given painting has a thin part from

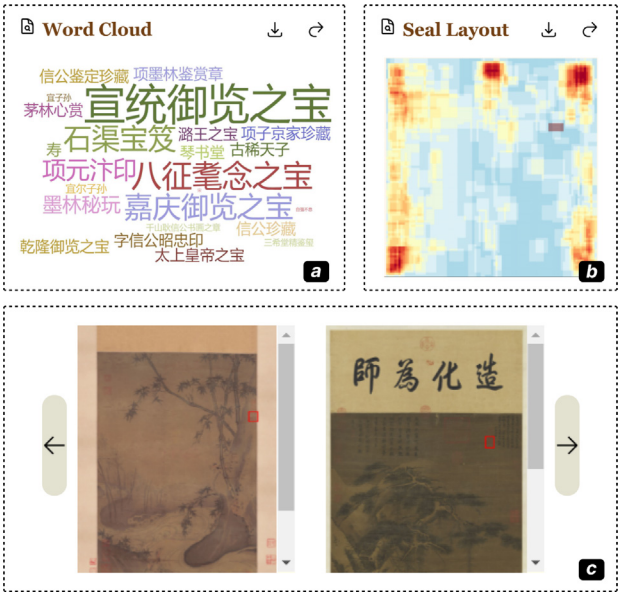

Fig. 4. We leverage (a) word cloud and (b) heatmap to present the layout and content overview of the inscriptions or seals. (c) The detailed content and context of the inscriptions or seals are provided through the heatmap selection.

paper to a vertical scroll, indicating that such a painting is drawn by this artist with a low possibility and inspiring further detailed examination.

4.3. Inscriptions and seals dimension

The position and content of inscriptions or seals are another important dimension for accurately determining whether a painting fits the established habits of an artist. We used a heatmap diagram and word cloud visualization to summarize the stamping habits of the artist and clearly show the bias of the authenticated painting (**G1**). As shown in Fig. 4b, the heatmap shows the frequency of placement of inscriptions or seals. The region with blue color represents a lower probability of occurrence. We normalized all paintings to the same size for position comparison. To show the layout bias, we put a bounding box on the heatmap that represents the position and size of the inscription or seal on the authenticated painting. For instance, the color within the bounding box is relatively bluer, indicating a greater suspicion of misalignment with its identity.

To support the exploration of the content of inscriptions or seals (**G3**), we enable users to examine the details of paintings in the selected region. As users select a region on the heatmap, our system will filter and show all paintings having their inscription or seal on that region, indicated by a red bounding box (Fig. 4c). Moreover, we employ the word cloud visualization to provide an overview of these contents (Fig. 4a), helping users identify the main textual information. Users can explore the layout of a specific inscription or seal by clicking on the corresponding text within the word cloud. The heatmap will then show the frequency of placement of the specific inscription or seal. These visualizations guide users in learning the likelihood of content occurrence in the given painting through the word cloud and support details on demand.

4.4. Painting techniques dimension

Most artists prefer distinct techniques that offer crucial clues to identify the painting of authentication. For example, an authentic painting should strive to closely resemble the unique

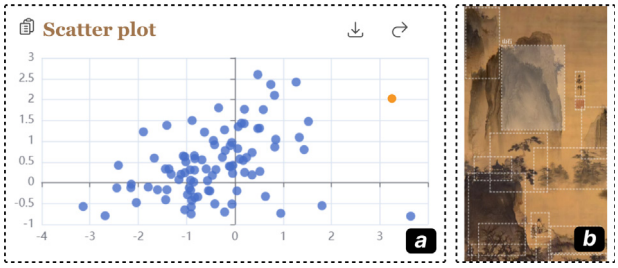

Fig. 5. Exploring the painting techniques. (a) The scatter plot presents the technique similarities among potentially related objects, where the selected object is highlighted in orange. (b) The painting view is coordinated with the scatter plot, which shows the object regions with dashed boxes and highlights the selected region.

original techniques employed by the claimed artist. To represent such a clue, we leverage the painting technique of embedding and scatterplot to visualize the closeness. Specifically, all objects (*mountain*) within the authenticated paintings and paintings in the database are identified and segmented as slices. These slices are mapped to a 512-dimensional vector by using CLIP Embedding (Radford et al., 2021) and projected to a two-dimensional vector. Based on the resulting 2D vectors, we utilize a scatter plot to show the slice similarity, where a closer dot pair indicates a more similar nature of the corresponding slices.

Our system enables related painting exploration to help users understand the clue (**G1** and **G3**). The painting view and the scatter plot are coordinated (Fig. 5). As users select an object denoted by a dashed box in the authenticated painting, its represented dot will highlighted, showing its similarity to its neighbors. Moreover, users can also explore these neighbor dots through the selection to check its objects and compare the image in detail, Therefore, it provides an interactive interpretation of the technique-related feedback.

4.5. Chat-based interactions

We propose a conversational view that creates a chain-of-thought user experience to authenticate the painting progressively. Similar to a common dialogue interface, all the texts and images submitted by users are shown on the right side, while the feedback provided by the agent is displayed on the left. Utilizing the capabilities of GPT, our system can offer user-centric guidance on utilizing ArtEyer. Those generated guidance are formed based on the user's input and the previous dialogue between the user and the agent. Users can also refer to the "Recommended Questions" section to help them get into the next step (Fig. 6).

To embed designed visualizations in the feedback, our system automatically detects the specific dimension the user is currently focused on. For instance, as ArtEyer detects that the user is required to understand the position of a seal, our system will insert the corresponding heatmap into conversations. Buttons to display or hide these visualizations are listed in the "Recommended Questions" part. These visualizations will help users to enhance their comprehension of the textual explanations and the paintings.

4.6. Implementation

ArtEyer is an interactive web-based application that includes a front end and a back end. The front end is built upon the Vue3 architecture, which is responsible for the visualization component and ensuring it is presented on various tablet devices in the form of web browsing. The back end is based on Django+Python

to achieve the agent component. We use Segment Anything,[4] a state-of-the-art picture segment model to obtain the local regions. To perform the GPT-based analysis, we call the GPT-4V API,[5] which can read images and process text inputs. To create visualizations, we employ EChart[6] with data transformed from raw data stored in a database. To fine-tune the GPT agents, we initially gathered five authentic paintings from each artist involved in our study. We then used Photoshop to create counterfeit versions of these artworks. Subsequently, collaborating experts were asked to summarize the features of each painting according to three authentication dimensions and to provide their authentication results. The summarized features, alongside the authentication results, served as ground truth for refining the sub-agents and the main agent through an instruction-based learning approach. From each artist, we selected one additional painting for the user study. The refined agents were then utilized to authenticate these four additional paintings.

5. Usage scenario

In this section, we present a practical usage scenario to demonstrate how ArtEyer effectively supports painting authentication for ordinary collectors.

Eddie, a businessman, recently received an ancient painting from a friend who claimed it was created by Ma Yuan, a renowned painter from the Song dynasty of China. To determine whether the painting is an authentic work by Ma Yuan, he photographs and uploads it to ArtEyer. After understanding Eddie's objectives, ArtEyer lists three dimensions for painting authentication and guides Eddie to select the desired one through recommended questions (Fig. 6a). Since Eddie lacks knowledge of painting authentication, he chooses the first dimension by clicking on its corresponding question. ArtEyer then presents a Sankey diagram that displays the distribution of basic attributes for Ma Yuan's paintings (Fig. 6b). Below the Sankey diagram, ArtEyer introduces the basic attributes of the input painting and subsequently summarizes whether these attributes are in line with those of Ma Yuan's paintings in sequence. By reading the explanation of the Sankey diagram, Eddie confirms that ArtEyer's analysis aligns with the data distribution presented in the diagram. However, he still feels confused about the specialized terms involved, such as "colored" and "light-colored". He enters the dialogue box: "What is the difference between 'colored' and 'light-colored'?" ArtEyer provides explanations for both terms and offers two examples to illustrate their differences. After that, Eddie believes that Ma Yuan could potentially create the input painting and decides to explore other dimensions.

Eddie clicks on the question "View authentication results under the seal dimension" at the bottom of the analysis of basic attributes. ArtEyer then presents a word cloud summarizing the text of seals and a heatmap demonstrating the positional distribution of seals in Ma Yuan's paintings (Fig. 6c). Below the visualizations, ArtEyer analyzes whether the seal in the input painting matches those in Ma Yuan's paintings. Upon learning the encodings of the two visualizations, Eddie confirms that ArtEyer's analysis ("the seal in the input painting is the high-frequency seals in Ma Yuan's paintings, but its stamped position appears to be unusual") aligns with the data facts revealed in the visualizations. To further determine whether the seal's stamped position is unusual, Eddie selects its corresponding location in the heatmap to view Ma Yuan's paintings that contain seals in that location. He finds that the six paintings he viewed all have wide mounts that encompass the selected location. Considering that the input painting does not have a mount, Eddie concludes that the position of its seal is unusual. Furthermore, he is curious about the actual position of the seal in Ma Yuan's paintings. Eddie clicks on the word in the word cloud corresponding to the seal to view Ma Yuan's paintings containing that seal. By observing these paintings, he finds that the seal is consistently placed at the top center of the paintings, which further suggests that the seal in the input painting is likely counterfeit.

Eddie continues to click on the question "View authentication results under the painting technique dimension" at the bottom of the seal analysis. ArtEyer relists the input painting and asks Eddie to select the specific objects he wishes to examine (Fig. 7a). After Eddie selects the mountain in the center of the painting, ArtEyer presents a scatter plot showing the similarity in painting technique between the selected mountain and mountains in Ma Yuan's paintings. Below the scatter plot, ArtEyer summarizes the selected mountain's painting technique and analyzes its differences from that of the mountains in Ma Yuan's paintings (Fig. 7b). Eddie is very interested in the painting techniques mentioned in ArtEyer's analysis. So, he selects a portion of the points in the scatter plot. By examining the slice of mountains returned by ArtEyer, Eddie further understands the technique differences described in the analysis (Fig. 7c). He believes that the input painting indeed does not match that of Ma Yuan's paintings in terms of painting technique. Finally, Eddie requests ArtEyer to summarize the authentication results (Fig. 7d). After considering the findings, he acknowledges the high probability that the input painting is counterfeit.

6. User study

This section presents a user study to evaluate ArtEyer.

Participants. We recruited 12 participants (6 males and 6 females) to complete the painting authentication tasks. Their average age was 24.4 years old (ranging from 21 to 40). They had diverse educational backgrounds, including computer science, industrial design, and traditional Chinese painting. All participants were able to read basic visualizations such as bar charts and had previous experience using large language models such as ChatGPT, but 7 of them had not utilized GPT 4.0 for image analysis. Notably, 4 participants possessed basic knowledge of elementary Chinese painting authentication, including familiarity with related terminologies and basic authentication methods, while the rest were unacquainted with Chinese painting authentication practices. Each participant received a $10 payment for the 1-hour user study.

Data and Tasks. We prepared four paintings for authentication, including two authentic paintings by ancient Chinese painters and two counterfeit paintings. Each of the four paintings is selected from each artist in our study. To simulate counterfeit paintings that one might encounter in the real world, we used Photoshop to edit authentic paintings, altering forms, positions of seals, and brushstrokes of painting techniques. These served as our counterfeit paintings in the study. We divided participants into two groups (referred to as Group A and Group B) in a counter-balanced order, ensuring similarity in gender, age, and familiarity with authentication between the two groups. Group A was randomly assigned one counterfeit painting, while Group B was randomly assigned one authentic painting. They were unaware of the authenticity of the paintings beforehand. Throughout the study, participants engaged in interactive dialogues with ArtEyer to explore various dimensions of the paintings, ultimately concluding that they were authentic. While conclusive evidence of counterfeiting in one dimension could lead to the conclusion that a painting is counterfeit, we still encouraged users to explore

[4] https://segment-anything.com/demo
[5] https://platform.openai.com/docs/guides/vision
[6] https://echarts.apache.org/en/index.html

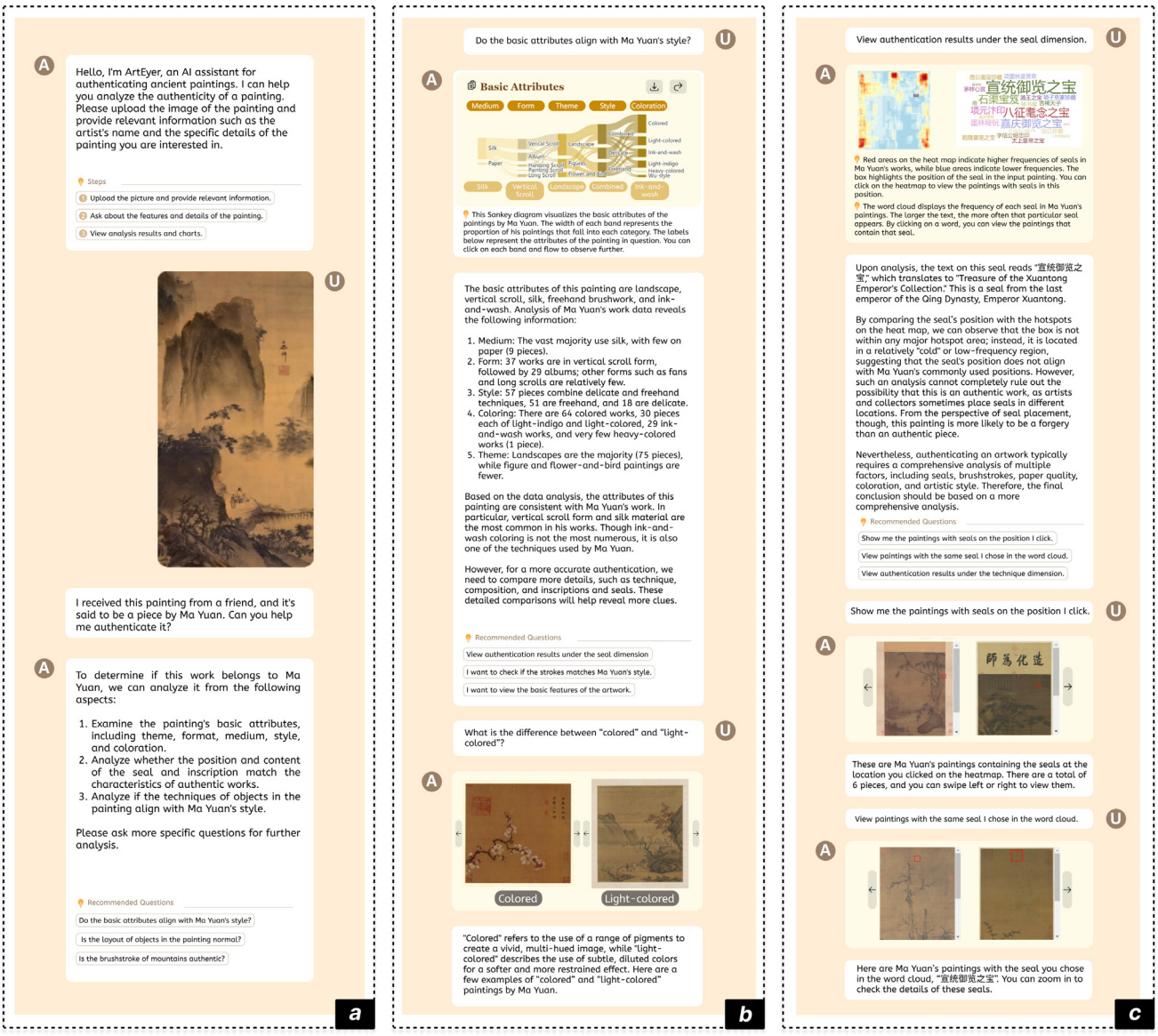

Fig. 6. Eddie's process of authenticating a painting with ArtEyer: (a) ArtEyer prompts Eddie to upload the painting's image and related information, providing some recommended questions. (b) Eddie chooses to analyze the basic attributes, and ArtEyer presents a Sankey diagram, concluding that the basic attributes align with Ma Yuan's habits. (c) Eddie further inquires about seal-related analysis. ArtEyer provides a heatmap and word cloud to assess the seal's content and position, revealing the seal is not in its usual location.

other dimensions of the painting to complete a comprehensive analysis.

Procedure. The study consisted of three stages: introduction and practice (20 min), formal task (30 min), and interview (10 min). In the first stage, participants were initially asked to fill out a basic information questionnaire. It collected data on their gender, age, academic background, and familiarity with painting authentication, visualizations, and GPT. Then, we introduced the background of this study and demonstrated the usage of ArtEyer. Following this, participants engaged in a practice task to freely explore the system, where they could seek our assistance at any time. Once participants had no further questions about the system, they would proceed to the formal task of identifying their assigned paintings. During this stage, we recorded whether participants correctly identified each dimension of the painting. After completing the formal task, participants were required to rate various indicators of the system in a questionnaire and participate in an interview.

Questionnaire and Interview. In the questionnaire (see Table 1), participants were asked to rate the system on a scale of 1 to 7, where 7 represented complete satisfaction (see Fig. 8). This rating encompassed various aspects, including ease of use and learning, the effectiveness of visualizations in different dimensions, and satisfaction and trust with the agent's analysis. We also conducted interviews with participants to understand the reasons behind their ratings and asked a few questions to gather their feedback on the system.

Results. To assess the performance of ArtEyer, we evaluated the trust of users in the authentication results presented by ArtEyer (Q_6). 12 participants gave an average score of 6.08, which indicated that ArtEyer was able to provide trustworthy authentication results. P8 stated, *"ArtEyer's rigorous logic and provided visualizations make it appear highly professional. Initially, I did not trust it. However, as I continually checked its authentication results by understanding data facts demonstrated in the visualizations, I found its analysis to be accurate, which increased my trust in it"*. Moreover, P2 commented that *"I noticed that ArtEyer sometimes made unfounded claims when authenticated paintings in painting technique dimension, particularly in its analysis of brushstrokes.*

Fig. 7. Eddie selects a mountain to analyze its technique: ArtEyer offers a scatter plot (a) and analyzes the differences in brushstrokes compared to Ma Yuan's style (b). It lists some mountain slices from Ma Yuan's paintings to support a one-by-one stroke comparison (c). Conclusion of the authentication process: The painting is likely to be a counterfeit, yet further expert consultation is advised (d).

Table 1
Questions in the subjective questionnaire.

	Evaluation of the overall system
Q1	ArtEyer is easy to learn.
Q2	ArtEyer is easy to use.
Q3	The prompts provided are helpful.
Q4	ArtEyer can answer the questions I want to know.
Q5	The summary of the authentication results is satisfactory.
Q6	I trust the authentication results by ArtEyer.
	Evaluation of the Three Dimensions
Q7	The visualization of this dimension is effective.
Q8	ArtEyer's analysis of this dimension is satisfactory.
Q9	The analysis of this dimension is effective for authentication.

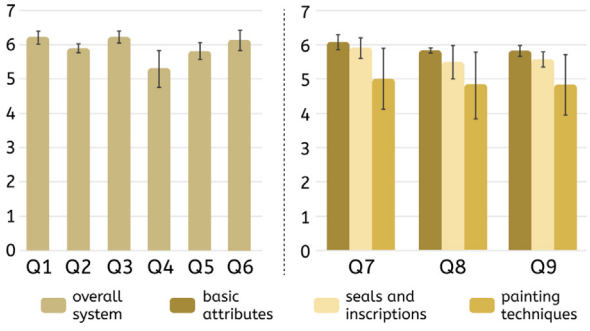

Fig. 8. Participants' evaluation scores for the overall system and three authentication modules.

When faced with such situations, I would manually review a batch of reference slices through the scatter plot. While this added an extra cognitive burden, it enabled me to make more confident judgments".

To further verify the effectiveness of ArtEyer, we calculated the accuracy of the participants' authentication results. Among the 6 participants in Group A tasked with identifying counterfeit paintings, 5 correctly identified the paintings as counterfeit. In comparison, among the 6 participants in Group B tasked with identifying authentic paintings, 4 provided correct outcomes. The three participants (P4, P6, P9) who provided incorrect authentications all made errors in analyzing painting techniques. For instance, P9 in Group A, when identifying a counterfeit painting purportedly attributed to Guo Xi, believed that different trees painted by the same artist might use different stroke patterns. Lacking definitive evidence of counterfeiting in other dimensions of the painting, P9 mistakenly identified the counterfeit as authentic. Notably, all three participants were unfamiliar with stroke patterns. In the case of basic attributes and seals, the visualization of reference data helped mitigate the impact of unreliable analyses caused by the hallucination issue in GPT on authentication results. However, the analysis of brush strokes involved subjectivity, making it more prone to errors, which aligned with our expectations.

Table 2
t-values for authentic and counterfeit groups.

Question	Authentic group	Counterfeit group
Q1	20.23	10.99
Q2	24.87	9.43
Q3	20.23	10.99
Q4	4.00	4.22
Q5	12.29	14.06
Q6	11.45	9.43
Q7	16.14	9.43
Q8	41.73	9.43
Q9	12.27	10.08

To enhance the evaluation of user performance in distinguishing between authentic and counterfeit paintings, we statistically analyzed questions Q1 to Q9 for two groups: one for authentic paintings and another for counterfeit ones. We conducted one-sample t-tests to compare the average scores against a neutral score of 11, aiming to verify if users' performance significantly exceeded chance levels. Since all the calculated t-values exceeded the critical value of 1.796 for a one-tailed t-test with 11 degrees of freedom at the 95% confidence level (see Table 2), we concluded that the ArtEyer system effectively assisted users in differentiating between authentic and counterfeit paintings.

Participants rated ArtEyer's *ease of learning* and *ease of use* positively, with average scores of 6.25 and 5.92, respectively. They also highly rated the prompts provided during interactions and the final summary of authentication results, which highlights the strengths of LLMs' text generation abilities. However, the question "*Can ArtEyer answer all the questions I want to know*" received a lower score. Although most participants followed the prompts given and ArtEyer was able to provide answers, two participants, due to their familiarity with Chinese painting authentication, raised more detailed questions, such as whether the clothing styles of characters matched the era. ArtEyer is currently not supporting this functionality.

The visualization and analysis of the basic attributes received positive feedback from participants (with average scores above 5.8). Participants tasked with identifying a counterfeit painting purportedly attributed to Liang Kai were able to analyze that the artist had never painted heavy-colored landscape paintings, a critical point in identifying counterfeit paintings. The inscription and seal module also received positive feedback (with average scores above 5.5). Two participants suggested seeing the overall layout rather than just individual objects. On the contrary, the feedback for the painting technique module was lower (with average scores ranging from 4.8 to 5). Although several participants believed that ArtEyer's analysis was well-founded, such as recognizing the difference between "fupi cun" and "juanyun cun", four participants did not trust GPT's results, feeling that the analysis language was too vague. The difficulty beginners face in discerning stroke patterns also contributed to this outcome.

User Feedback. Through interviews, we gathered valuable feedback from participants across various aspects, such as GPT-driven authentication, visualization, and interaction.

GPT-driven Authentication. All participants acknowledged GPT's ability to analyze paintings. Some of them also expressed approval of its analysis of stroke patterns. For instance, P5, who had not previously experienced the capabilities of GPT in analyzing images, was impressed at its ability to differentiate stroke patterns after using our system, stating, *"If GPT is provided with more professional knowledge, the results would be incredibly effective"*. P4 previously mentioned that the stroke patterns of mountains/trees in an artist's paintings may differ; for example, if clouds obscure a mountain, the stroke patterns may appear softer, so dissimilarity in stroke patterns between a painting and other works by the same artist may not necessarily indicate counterfeit. The collaborating experts were also impressed by GPT's powerful authentication capabilities. EA remarked, *"I was surprised by GPT's ability to identify different brushwork styles, although its summary of the technical characteristics was not entirely complete"*. EB also mentioned, *"GPT does not use overly assertive language when presenting authentication results, which aligns with the basic requirements of fundamental authentication tasks"*.

Regarding the question "*Under what circumstances would you use ArtEyer?*" interesting responses were obtained. Many participants mentioned that this system was a good analytical and guiding tool for antique collectors unfamiliar with art authentication. P3 mentioned recommending this system to one of his father's friends, who enjoyed collecting antique paintings. P7 believed that even if one did not need to identify paintings but wanted to understand an artist's style, this system could be of good use. However, some participants noted that while the system could analyze basic information, consulting experts was still necessary for detailed stroke pattern authentication.

Visualization and Interaction. The visualization design in ArtEyer received unanimous praise from participants, who found it to be intuitive and effective in aiding authentication. For instance, P8 stated, *"The visualizations in ArtEyer analyze various aspects of paintings from macro to micro dimensions, enhancing my perception of the data"*. ArtEyer's interactive attributes also received positive feedback from users, being described as *"innovative"*, *"user-friendly"*, and *"capable of providing real-time feedback"*. Many users currently recognize talking with a GPT as a mainstream interaction method; however, attributes in our system, such as clicking on images to receive feedback, are functions that GPT currently does not support. P9 mentioned, *"Using this interaction, the amount of information obtained with just one click far exceeds expectations"*. However, P6, who is very familiar with traditional visualization systems, pointed out that embedding interactive attributes in GPT conversations is not as convenient as traditional *visualization systems, stating, "Typing is slower than clicking with a mouse, and reading text is slower than reading charts"*. Nonetheless, he acknowledged that this system is user-friendly for those unfamiliar with visualization.

7. Discussion

Enhancing Accessibility and Educational Impact with Visualization. The integration of explainable data visualizations within ArtEyer not only democratizes the art authentication process but also imbues it with a depth of insight and educational value previously unattainable. By distilling complex, often elusive data points into comprehensible visual narratives, ArtEyer empowers users to traverse the intricate landscape of art authentication with newfound clarity and confidence. This leap forward in accessibility is pivotal, as it not only facilitates more informed decision-making but also cultivates a more nuanced appreciation of art. Moreover, ArtEyer's capacity to dismantle long-standing illusions and biases inherent in traditional authentication methodologies underscores the transformative potential of visualization technology in reshaping our interaction with cultural artifacts. As such, ArtEyer emerges not merely as a tool for authentication but as a beacon for education and enlightenment within the art community.

Fostering GPT Innovations for Complex Real-World Applications. The integration of GPT into ArtEyer transcends a mere technological achievement, heralding a significant shift in the methodologies employed to address problems entrenched in subjective judgment and rich historical contexts. This shift is particularly pronounced in the realm of art appraisal, where GPT is leveraged to navigate the complexities inherent in evaluating artworks (Jin et al., 2024), which are often steeped in historical, cultural and aesthetic significance. GPT excels in parsing and synthesizing extensive datasets (Lv et al., 2024; Wang et al., 2024)—including art historical texts and auction records—to emulate human cognitive processes. Thus, it offers insights that align closely with the expert understanding of art, effectively bridging the gap between computational efficiency and humanistic insight.

ArtEyer's innovative use of GPT technologies marks a paradigmatic transition from perceiving these tools as mere data processors to valuing them as intellectual collaborators in the art authentication process. GPT's ability to digest and analyze a broad spectrum of information enables them to draw connections and identify patterns that might escape even the most experienced connoisseurs. This capability not only enhances the process of authenticating art by identifying stylistic consistencies and discrepancies but also illustrates the broader applicability of GPT as transformative agents in solving complex, real-world challenges. Although it is currently impossible to fully evaluate GPT's performance in painting authentication tasks due to the lack of relevant datasets, the capabilities it has demonstrated still inspire imagination about the future of personalized authentication services. By demonstrating their utility in art authentication, GPT underscores their potential to revolutionize problem-solving in diverse fields where understanding nuance, context, and subjective interpretation are paramount, such as legal analysis and

cultural heritage preservation. Thus, they expand the horizons of what can be achieved through the synergy of computational power and humanistic insight.

Navigating Subjectivity and Uncertainty in Art Authentication. Art authentication is a field fraught with subjectivity and interpretive variability, as illustrated by the conflicting opinions of leading experts on Zhao Ji's "Hibiscus and Golden Pheasant". Wu Hufan's rejection of the piece as a counterfeit, juxtaposed with Xu Bangda's acceptance of its seals and colophons but not the painting itself, and Ding Yiyuan's complete endorsement of its authenticity, highlight the subjective underpinnings of art evaluation. This scenario underscores a critical issue: the authentication process is significantly swayed by personal views on the alignment of certain features with an expected standard.

While ArtEyer offers innovative visual tools to clarify the distribution of data crucial for determining authenticity, it operates within a realm filled with personal biases. The challenge of setting clear criteria for what constitutes an "authentic" characteristic remains, and this is heavily influenced by an appraiser's personal interpretation. This variability in judgment calls for a more sophisticated method of defining and navigating the parameters that underpin the authentication process. Additionally, art authentication is often marked by uncertainty, especially when an artwork displays consistent techniques in most aspects but shows anomalies in others. This situation requires a holistic authentication approach, where multiple facets need to be considered. However, the lack of clear-cut evidence introduces uncertainty to the authentication conclusions. ArtEyer's hesitance to deliver definitive judgments in ambiguous situations reflects a more significant issue within art authentication: the ongoing challenge of balancing the use of technology with its inherent limitations in making conclusive assessments.

Diversity and Complexity of Artwork Authentication Dimensions. The realm of artwork authentication is marked by a rich tapestry of dimensions that extend well beyond the three points discussed in this study. Connoisseurs and experts frequently rely on a broader spectrum of criteria, including the type of paper, the pigments used, and the inscriptions or texts associated with the artwork. These dimensions play a critical role in determining the authenticity of a piece, offering insights into its provenance, the era of its creation, and the artist's unique methods and materials. To accommodate the nuanced demands of these additional dimensions, ArtEyer must embrace a more comprehensive approach, incorporating a wider array of inputs, reference materials, and, crucially, sophisticated visualizations. This expansion will enhance the tool's accuracy and relevance to artwork authentication.

Beyond expanding authentication dimensions, there is an imperative need to delve deeper into the complexity inherent in the dimensions currently supported by ArtEyer. For instance, the intricate relationships between different seals or chops affixed to a painting reveal a hierarchical structure that reflects historical and familial ties among Chinese emperors, such as the relationship between Qianlong and Xianfeng. Therefore, seal positioning is not arbitrary but bound by cultural and temporal constraints, offering a wealth of information for those able to decode it. Similarly, the examination of painting techniques must account for individual artists' unique expressions and stylistic nuances, which are often most evident in the subtleties of brushwork.

Tailoring Authentication Processes to Painting Genres. Future work for ArtEyer includes refining its authentication process to cater specifically to different types of paintings, recognizing that the most pertinent dimensions for authentication vary significantly across genres. The current approach of presenting all possible dimensions for user exploration can overwhelm users and hinder their ability to quickly identify the most critical aspects for authentication. Experts suggest that, for instance, the authentication of court-fine brushwork paintings prioritizes the analysis of painting techniques due to stringent technical requirements. In contrast, the analysis of literati paintings might focus on inscriptions first, given the artists' backgrounds in scholarly pursuits rather than in skilled painting techniques. Tailoring the authentication process to align with the unique characteristics and historical contexts of each painting type could significantly enhance ArtEyer's efficiency and accuracy. To achieve this goal, future efforts should first summarize the authentication processes of different painting genres and then allow ArtEyer to dynamically recommend the sequence of authentication dimensions. This customization would not only streamline the authentication process but also provide users with a more intuitive and focused exploration of artworks, ultimately leading to more meaningful and informed conclusions about their integrity.

Incorporating Temporal Dynamics for Enhanced Precision. Future iterations of ArtEyer will need to incorporate time-based analysis to enhance its authentication accuracy. The current visualization strategy presents all pertinent information simultaneously, overlooking the critical aspect of temporality. For instance, artists' use of seals and the characteristics of their painting techniques can vary significantly over different periods. Segmenting the information related to authentication dimensions into more granular time-based units could facilitate a more precise authentication process. Thus, future developments should focus on integrating temporal visualizations that support analysis along the time dimension. For example, flow-based visualizations (Straub et al., 2024; Qiu et al., 2024; Shirato et al., 2023; Zhu et al., 2023) are usually used to illustrate the temporal distribution of various data. These approaches will refine the process of distinguishing between authentic and counterfeit works and provide users with a deeper understanding of an artist's evolution over time (Zhang et al., 2024; Tang et al., 2023).

Generalizability and Applicability. ArtEyer's methodology is a general technical framework that can easily be applied to analyzing other artists' paintings and various types of cultural heritage artifacts (e.g., sculptures and ceramics) as long as the agents are adjusted with domain-specific data. However, certain specialized domain requirements may necessitate the design of new visualizations and interactions. Furthermore, the visualizations in ArtEyer may make it difficult to display the feature distribution of large-scale reference materials due to potential visual occlusion issues. Future work should consider utilizing multi-scale visualizations (Wen et al., 2024; Rasheed et al., 2023; Deng et al., 2024) to address this problem. Currently, ArtEyer can only determine a painting's authenticity by comparing its feature distribution with that of known authentic paintings. Therefore, for authentic paintings whose features fall outside the distribution or counterfeit paintings whose features fall within it, future work needs to expand the dimensions of authentication and provide ArtEyer with deeper domain knowledge to enhance its ability to handle these complex cases.

8. Conclusion

We collaborate with professionals to develop ArtEyer, a GPT-based agent that leverages contextual data visualizations to facilitate the easy authentication of paintings. We carefully craft data visualizations to expose vital insights for authentication, which we subsequently utilize to augment the conversational interface of ArtEyer. These contextual visualizations serve as explainable answers that can enhance user trust and also allow users to directly interact with data items to generate precise prompts. Finally, we introduce a use case to demonstrate ArtEyer and conduct a user study, which involves a diverse group of participants to gauge user experience and system performance.

CRediT authorship contribution statement

Tan Tang: Conceptualization, Methodology, Supervision, Writing – review & editing. **Yanhong Wu:** Investigation, Writing – original draft. **Junming Gao:** Software, Writing – review & editing. **Kejia Ruan:** Data curation, Writing – review & editing. **Yanjie Zhang:** Visualization. **Shuainan Ye:** Writing – review & editing. **Yingcai Wu:** Funding acquisition. **Xiaojiao Chen:** Funding acquisition, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Ethical approval

This study does not contain any studies with human or animal subjects performed by any of the authors.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.visinf.2024.11.001.

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