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Learning-Based Artificial Intelligence Artwork: Methodology Taxonomy and Quality Evaluation

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With the development of the theory and technology of computer science, machine or computer painting is increasingly being explored in the creation of art. Machine-made works are referred to as artificial intelligence (AI) artworks. Early methods of AI artwork generation have been classified as non-photorealistic rendering, and, latterly, neural style transfer methods have also been investigated. As technology advances, the variety of machine-generated artworks and the methods used to create them have proliferated. However, there is no unified and comprehensive system to classify and evaluate these works. To date, no work has generalized methods of creating AI artwork including learning-based methods for painting or drawing. Moreover, the taxonomy, evaluation, and development of AI artwork methods face many challenges. This article is motivated by these considerations. We first investigate current learning-based methods for making AI artworks and classify the methods according to art styles. Furthermore, we propose a consistent evaluation system for AI artworks and conduct a user study to evaluate the proposed system on different AI artworks. This evaluation system uses six criteria: beauty, color, texture, content detail, line, and style. The user study demonstrates that the six-dimensional evaluation index is effective for different types of AI artworks.

CCS Concepts: • **General and reference** → **Surveys and overviews**;

Additional Key Words and Phrases: AI art, artwork, style transform, painting, methodology taxonomy, quality evaluation

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1 Introduction

In the late 19th century, the emergence of photographic technology stimulated artistic diversity. In the early 1990s, the successes of photorealistic computer graphics encouraged alternative techniques for non-photorealistic styles of rendering [81, 82, 124, 142]. Recently, creation of computer artworks has become popular along with related research studies, and new advances in machine learning and deep learning have led to an acceleration in the development of **artificial intelligence (AI)** artworks [12]. In this review, we consider state-of-the-art methods in AI artworks—that is, non-photorealistic creative drawings or paintings generated by AI models.

Many artists and computer researchers have used technologies and methodologies for automatically transforming images into synthetic artworks. Since the 1990s, **stroke-based rendering (SBR)** methods first proposed by Haeberli [48] have become popular in computer-generated artwork. In 2003, Hertzmann [54] reviewed SBR algorithms and art styles of machine paintings. Although diverse SBR methods offer many types of art style for synthesized artworks, these methods require significant use of computer memory and are time consuming. With the development of machine learning and reinforcement learning, methods and technologies addressing AI artworks optimize these issues. In 2013, Kyprianidis et al. [81] reviewed technologies and methods of **non-photorealistic rendering (NPR)** that transferred input photographic images or videos into non-photorealistic stylized results. Latterly, Jing et al. [70] investigated **neural style transfer (NST)** methods that belong to the field of NPR. Their work extended the review of NPR based on the work of Kyprianidis et al. [81]. However, to date, no work has generalized the methods of creating AI artwork including learning-based methods for painting or drawing. Moreover, the evaluation of AI artwork methods is not systematic. Researchers have tended to use their own evaluation methods to compare their own work with prior works. However, a reasonable and consistent evaluation system is important for fair comparison of the differing methods of generating AI artworks. Although Jing et al. [70] summarized the current approaches to evaluating NPR artworks, most evaluation approaches are not suited to different algorithms. It is necessary to develop a consistent evaluation system for diverse styles of AI artwork.

To solve the preceding problems, we investigate current learning-based methods for AI artworks and classify these methods according to different art styles. Furthermore, inspired by art vocabulary [134] and the representation of art paintings [22], we propose a consistent evaluation system for AI artworks and conduct a user study to evaluate the adaptability of the evaluation system. The proposed evaluation system contains six criteria: beauty, color, texture, content detail, line, and style. In particular, since beauty [107] is a dominant factor in the judgment of artwork by humans, we set a weighting of 50% of the score for beauty, and the other five aspects account for 10% each, respectively. The results of the user study indicate that the proposed evaluation system is effective for different types of artworks, and the score distribution also demonstrates that the percentage setting is reasonable. Based on the analysis of the current methods and experiments on the evaluation system, we propose and analyze challenges and opportunities for AI artworks as well as areas of possible development.

We summarize the contributions of this survey as follows:

- We investigate recent works on existing AI artworks and classified these according to different art types to produce a clear taxonomy and consistent evaluation.
- We propose a unified evaluation system for different AI artworks to ensure fair comparison of different AI models.
- We analyze challenges and opportunities for the development of AI artworks.

The article takes into consideration methods, art styles, and the evaluation system. To ensure the comprehensiveness and reliability of the literature review, we collected relevant literature from

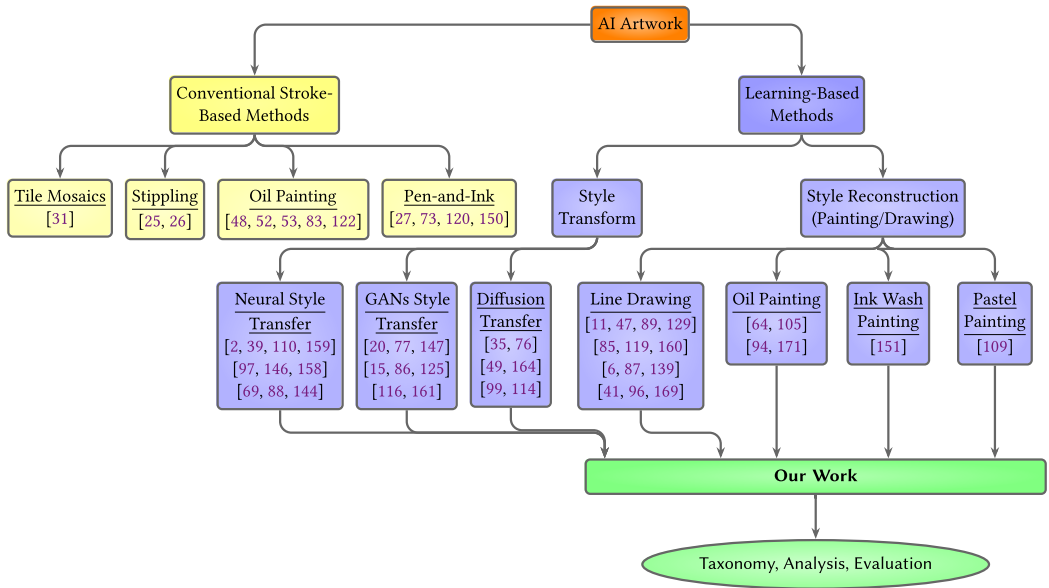


Fig. 1. Taxonomy of AI artwork based on methods and art styles.

multiple databases, including Google Scholar, IEEE Xplore, ACM Digital Library, and arXiv. Our keywords included “artificial intelligence art,” “deep learning,” “generative adversarial networks (GAN),” “diffusion model,” “computer vision,” “creative generation,” “line drawing,” “oil painting,” and “stroke.” The search range was limited to publications from 2015 to 2024 to provide bounding of information but also ensure the timeliness and relevance of the literature. The initial search yielded about 2,500 papers, and an additional 50 papers were identified from other sources. After removing duplicate entries, we screened 600 papers. By reading the titles and abstracts, we excluded 300 less relevant papers, leaving 300 papers. We then conducted a full-text review of these remaining papers and excluded 100 that did not meet the inclusion criteria. Ultimately, we selected 200 highly relevant papers as the basis for this study.

As Figure 1 shows, AI artworks are classified into two preliminary categories based on the method used: conventional stroke-based methods and learning-based methods. Since conventional stroke-based methods have been extensively investigated and we mainly focus on learning-based methods, we only discuss conventional stroke-based methods briefly, in Section 2. We further categorize learning-based methods into style transformation and style reconstruction (painting/drawing) based on the way the style is produced. In each category, the number of references is extensive. Due to space constraints, we have selected only a subset to represent each category. Section 3 introduces the concepts and related methodologies of learning-based AI artworks. As stated in Section 3, we categorize and analyze current research on AI artwork based on neural networks in Section 4. Section 5 presents the resultant evaluation system for AI artworks and the experimental results to test the system on different methods. We aim to build a standardized, comprehensive evaluation system in follow-up studies. This evaluation system is able to evaluate various types of AI artworks adaptively. In Section 6, we analyze the opportunities and challenges of AI artworks while pointing out possible ways to address them in the not-too-distant future. Finally, we present the conclusions of this article in Section 7 and propose several worthy issues for future research. For a further discussion, we provide a supplement to discuss the application of AI art and the ethics and artistic integrity for AI art.

2 Conventional Stroke-Based AI Artworks

Conventional SBR methods mainly reconstruct images into non-photorealistic imagery with stroke-based models. Researchers have proposed many SBR methods adapted to different types of artwork, such as paintings [48, 52, 53, 83, 122], pen-and-ink drawings [27, 36, 148, 150], and stippling drawings [25, 26]. Haeberli [48] introduced a semi-automatic painting method based on a greedy algorithm commonly used for SBR. This work shows that different stroke shapes and stroke sizes can be used to draw paintings with different styles; however, this method needs substantial human intervention to control the stroke shapes and select the stroke location. Hertzmann [52] also proposed a style design for their painting method by using spline brushstrokes to *draw* the image. They used a set of parameters to define the style of the brushstrokes. The painting effects can be changed when the parameters are altered by the designer (user). Thus, this method requires users to have a high level of drawing skill. Lee et al. [83] proposed a method to segment an image into areas with similar levels of salience to control the brushstrokes. The detail level of brushstrokes in the salient area can be increased to improve the realism of painterly rendering, although users are also required to control the number of levels. Other researchers also proposed pen-and-ink drawing and stippling drawing methods [25–27, 36, 148, 150] to improve the drawing effect. Most of these methods decompose strokes utilizing a greedy algorithm [54] into steps and require substantial human intervention.

Most SBR methods are relatively slow, so their usability is limited, especially in interactive applications [54]. It is also difficult for inexperienced or unskilled users to choose key parameters in SBR methods to produce satisfying paintings. Moreover, SBR methods can generate a limited number of styles, making them inflexible.

3 Learning-Based AI Artworks

Learning-based AI artworks are non-photorealistic images reconstructed by deep neural networks. We classify learning-based AI artworks into two categories: end-to-end image reconstruction by style-transform models and drawing/painting with digital strokes by art-style-reconstruction models.

3.1 Style-Transform AI Artworks

Style-transform methods mainly focus on reconstructing an image into another visual style according to a reference style image or a style image dataset. Image NST methods take a content image and a style image as the input and then output a stylized result containing the content features of the content image; the visual representation of this stylized result looks like the style image. Most **generative adversarial network (GAN)**-based methods transform the input image into another style image according to the style of the training dataset. The output image contains its own content and presents the visual style in the same style as the dataset.

3.1.1 Neural Style Transfer. NST is a prototypical style-transform AI artwork method. Figure 2 shows an NST result generated by Gatys et al. [38]. NST works in an image-to-image manner, extracting texture features from a style image and content features from a content image, then fusing them to synthesize a new image. Modeling the style image and extracting its texture features is crucial. The goal is to reconstruct an image with the style textures from the style image while preserving the content of the content image.

The NST method, introduced in the work of Gatys et al. [38], uses **convolutional neural networks (CNNs)** to transfer style texture to a target image while resolving its content. The Gram matrix models the style image's representation, and the pre-trained VGG network's high-level features represent the content image. By minimizing content and style losses, the method synthesizes

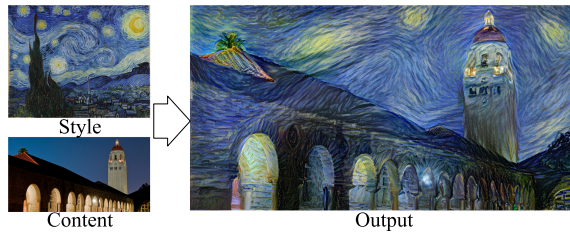


Fig. 2. Sample of results generated by the NST method [38].

an image with both input images' content and style. However, this style representation focuses on texture rather than global arrangement, resulting in unsatisfactory results for long-range symmetric structures. Berger and Memisevic [5] improved this by imposing a Markov structure on high-level features. The StrokePyramid module of Jing et al. [69] considers receptive field and scale, producing variant stroke sizes.

NST-generated images often have hard style features, making them appear unnatural. Careful selection of input-style images is essential to avoid unattractive results.

3.1.2 GAN-Based Style Transfer. GANs, introduced by Goodfellow et al. [42], have been widely applied in various research fields. GANs consist of a generator and discriminator, trained in an adversarial manner. The generator learns to produce realistic images, whereas the discriminator aims to distinguish between real and generated images. This minimax optimization process ends at a saddle point, balancing the two networks. GANs generate visually compelling fake images, blending authenticity with novelty.

GAN-based methods have revolutionized AI art, with notable applications like CycleGAN [170], AttentionGAN [132], and Gated-GAN [14]. These models learn the style features from datasets, transforming real photos into artistic styles without harsh style features. However, GAN-based methods have their drawbacks: the difficulty of training, large model size, sometimes poor detailed representation, and even mistakes.

3.1.3 Diffusion Model Style Transfer. **Diffusion model (DM)** style transfer represents a major breakthrough in AIGC (Artificial Intelligence Generated Content). It harnesses the power of DMs, which transform random noise into novel data samples through a unique stochastic diffusion process. This technology has fueled the rise of AI drawing platforms like OpenAI's DALL·E 2 [84, 111] and Google's Imagen [118], showcasing their remarkable image generation capabilities. In style transfer, DMs apply their generative prowess to imagery, enabling the seamless transformation of any input image into a specified artistic style. Their working mechanism seamlessly integrates noising and denoising processes, gradually degrading and then reconstructing the image with the desired style while preserving its original content.

This approach not only offers exceptional controllability, allowing users to fine-tune generated images with precision, but also guarantees diversity and flexibility. It effortlessly accommodates a wide spectrum of style requirements and reference images, yielding results ranging from photorealistic fakes [8, 49, 113, 118] to artistic interpretations [35, 49, 76, 99, 114, 164]. Furthermore, DMs exhibit remarkable stability and robustness, consistently producing high-quality stylized images even under noisy or varying input conditions. This reliability has sparked interest in research exploring partial image re-editing [51, 80], further underscoring the versatility of this technology.

3.2 Art-Style-Reconstruction AI Artworks

In this article, we refer to art-style-reconstruction AI artworks as those images that are generated via simulated strokes. Note that the art style is neither transferred from the style image nor learned

from the dataset: it is determined by the elements rendered onto the canvas. Therefore, when the models use different strokes to render the canvas, the generated image presents a different style. We first propose the concept of art-style-reconstruction AI artworks for these methods. It is important to recognize the difference between style-transform methods and style-reconstruction methods for AI artworks. Style-transform methods do not consider the generating process of the result, whereas style-reconstruction methods with simulated strokes pay significant attention to the generating process, since the result is built by strokes. For fairness, methods in these different categories should be evaluated by different evaluation metrics. According to the types of style, we classify art-style-reconstruction AI artworks into line drawings, oil paintings and watercolor paintings, and ink wash paintings.

3.2.1 Line Drawing. Line-drawing artworks such as sketches [6, 11, 47, 85, 89, 119, 129, 160], pencil drawings [87], portraits [96, 139], and doodles [105, 169] are created by line strokes. Significant research has been undertaken on line-drawing methods. Many studies have concerned the generation of line-drawing artworks by reconstructing input photos into line drawings. Compared with the input photos, generated line drawings lose much detailed content but retain the key contour of the object. Photo-sketch methods are mainly focused on the approach for capturing the contour information of an object in a photo, then mimicking the human sketching process to present the object. We usually consider photo-to-sketch synthesis as a cross-domain reconstruction issue. For example, Song et al. [129] constructed a generative sequence model with a **recurrent neural network (RNN)** acting as a neural sketcher. Their neural sketcher reconstructed a photo into a synthesis sketch by learning the noisy photo-sketch pairs dataset. Many methods for reconstructing photos into line drawings have been proposed. Line-drawing methods emphasize extracting the edge features of the object but not paying attention to the image's color information. In particular, when comparing methods of line drawings, the key point is the line stroke or the shade drawn by line strokes. Portraits and pencil drawings (except with colored pencils) similar to sketches usually have black-and-white color characteristics.

3.2.2 Oil Painting and Watercolor Painting. Painting is an important form of visual art. Oil painting and watercolor painting, distinct from line drawings, emphasize color and tone. The essence of painting is color, which is made up of hue, saturation, and value, dispersed over a surface. In generating oil paintings and watercolor paintings, mimicking the color and stroke texture of paintings is a main task for the reconstruction of image to painting. With deep learning coming into widespread use, researchers have conducted studies on training machines to learn to paint like human artists. In particular, Mellor et al. [105] proposed a neural network SPIRAL++ to doodle human portraits. The style of the generated image is close to that of an oil painting, although the results lose detailed content. Jia et al. [68] proposed a self-supervised learning algorithm to achieve painting stroke by stroke, and the results outperformed SPIRAL++ on the presentation of details, although the detailed contents were still not sharp. Huang et al. [64] designed a painting model based on reinforcement learning to mimic the painting process of a human artist. The color strokes rendered onto the digital canvas in a certain order made their generated images similar to oil paintings, although the texture of the strokes was different from human artists' strokes. Zou et al. [171] proposed an automatic image-to-painting model that generates oil paintings with controllable brushstrokes. The authors reframed the stroke prediction as a parameter searching process so that it mimicked the human painting process. Schaldenbrand and Oh [123] also proposed a model using **Content Masked Loss (CML)** to generate paintings stroke by stroke, although they lost some detailed contents of the image. For the stroke-based methods, the key point is how to present the detailed contents of the input image when reconstructing it to the painting stroke by

stroke. The problem is that retaining as many details as possible will produce a close-to-photo result instead of a painting.

3.2.3 Ink Wash Painting. Ink wash painting is a type of Chinese ink brush painting that uses black or colored ink in different concentrations. The stroke texture and character of ink wash painting are so different from that of oil painting and watercolor painting that teaching a machine or computer to do ink wash painting is difficult. Research has been conducted on methods to simulate the special stroke of ink wash painting. For example, in a conventional stroke-based method in the work of Yao and Shao [34], B-spline curves were used to simulate the trajectory of the Chinese brush. This method inspired later researchers to improve the simulation of Chinese brushstrokes for deep neural networks. Xie et al. [151] first modeled the tip of the Chinese brush and then utilized a reinforcement learning algorithm to formulate the automatic stroke generator.

3.2.4 Robotic Painting. Robotic painting, an intersection of art and robotics, has seen significant advancements. Researchers and interdisciplinary artists have employed various painting techniques and human-machine collaboration models to create visual media on canvas. Although robot paintings differ from the AI artworks discussed in this work, they share some similarities. Robotic painting requires the use of physical robotic arms or robots to complete stroke-by-stroke painting, ultimately resulting in physical paintings. However, the AI paintings discussed in this article are almost exclusively electronic versions and do not require the use of robotic arms or robots. Their similarity lies in the stroke-by-stroke painting algorithm, as most AI models for stroke-by-stroke painting, after processing, can be applied to robotic painting. Nevertheless, since the focus of this article is not an in-depth exploration of algorithms, in Section 4.4.5 we conduct a more comprehensive analysis and discussion on robotic painting.

4 Methods Comparison

For different types of AI artworks, we have classified existing research into several categories based on artistic types. Correspondingly, we propose an algorithm taxonomy according to the different types of AI artwork. We first classify AI artworks into two categories according to the generating process mentioned in Section 3. This section explains the algorithms of different methods for different types of AI artwork.

4.1 NST Method

DeepDream [1] first synthesized artistic pictures by reversing CNNs' representations with image-style fusion through online image reconstruction techniques. This method aimed to improve the interpretability of deep CNNs by visualizing patterns that maximize neuron activation. Although producing a psychedelic and unrealistic style, it became popular for digital art. Subsequent methods [38–40, 46, 62, 63, 71, 88, 100, 101, 117] optimized digital art by combining visual-texture-modeling techniques with style transfer, inspiring the proposal of NST. The basic idea is to model and extract style and content features from input style and content images, respectively, then recombine them into a target image through iterative reconstruction to produce a stylized result with features of both images.

Generally, image-style fusion NST algorithms share the same image reconstruction theory but differ in techniques to model the visual style. For example, some methods [97, 146, 154, 157] adjust parameters to tune the style or content ratio, whereas others [9, 69, 79, 142, 158, 159] control stroke size to represent the stylized results. A common limitation is their computation-intensive nature due to the iterative image optimization procedure.

The classical NST algorithm by Gatys et al. [38] reconstructs representations from intermediate layers of the VGG-19 network, showing that CNN-extracted content and style representations are

separable. The algorithm combines these features to synthesize a new image displaying both the style and content of the original images. The detailed algorithm is as follows.

Given a pair of images, the content image (I_c) and the style image (I_s), the algorithm of Gatys et al. [38] synthesizes a target image (I_t) by minimizing the following function:

$$\tilde{I} = \arg \min_{I_t} \alpha \mathcal{L}_c(I_c, I_t) + \beta \mathcal{L}_s(I_s, I_t), \quad (1)$$

where \mathcal{L}_c is the content loss between the content image and the generated target image, and \mathcal{L}_s is the style loss between the style image and the synthesized target image. The parameters α and β tune the ratio of content and style in the target image. Although tuning α and β changes the visual expression of the result, it does not allow for detailed style texture adjustments.

Further methods proposed controlling model parameters to achieve different stylization outcomes. Virtusio et al. [142] introduced intuitive guidance and artistic control on style-transfer models by adjusting pattern density and stroke strength. Based on the style transfer concept of Gatys et al. [38], this method also minimizes content loss and style loss, as shown in Equation (1), but with a different style loss definition in Equation (2c). In particular, Equation (2a) defines the centered Gram matrix, Equation (2b) is the style representation by Equation (2a), and δ_l controls the importance of each network layer. X denotes the input, and $\varphi_{(l)}(X)$ denotes the feature activation from the VGG-19 network:

$$Gram_c(X) = \mathbb{E}[(X - \mathbb{E}[X])(X - \mathbb{E}[X])^T], \quad (2a)$$

$$f_s(X, l) = Gram_c(\varphi_{(l)}(X)), \quad (2b)$$

$$\mathcal{L}_s = \sum_l \delta_l \|f_s(I_t, l) - f_s(I_s, l)\|_2^2. \quad (2c)$$

To control the visual effect of the stylized results, research has proposed using *stroke size*, *style scale*, or *pattern density* to control the artistic style in the synthesized image. These methods adjust the graininess of style feature representation to change the visual art effect. In the work of Virtusio et al. [142], *pattern density* controls stroke sizes, frequency, and graininess overall for the entire image through style resolution changes and variance-aware adaptive weighting. Pattern density is inversely proportional to image resolution size, and variance-aware adaptive weighting prioritizes dense pattern features to affect style representation. Additionally, Virtusio et al. [142] used *pattern density* and *stroke strength* together to control the art style, defining stroke strength as the salience of texture edges to tune without affecting other features.

While pattern density and stroke strength can adjust the visual performance of the stylized image, such as sharpening or lightening edge details, or zooming in or out on the style pattern grain, they cannot change the percentage of style or content features in the results. This highlights the need for more flexible methods that allow detailed adjustments of both style and content features.

4.2 GAN Method

4.2.1 Per-Model-Per-Style. GAN is a min-max game between two neural networks with different objectives. One network, the generator (G), aims to trick the other, the discriminator (D), by generating images that resemble the dataset from a random latent vector z . The objective of G is to create images closer to the dataset, whereas D tries to distinguish between real and generated images. Both networks optimize their tasks according to their objective functions. The dataset image is denoted as x , and $D(x)$ represents the probability that x is from the dataset. $G(z)$ denotes the image generated by the generator, and the cost for G is $\log(1 - D(G(z)))$. The overall loss

function is

$$\mathcal{L}_{\text{GAN}} = V(D, G) = \mathbb{E}_{x \sim p_{\text{data}}(x)}[-\log(D(x))] + E_{z \sim p_z(z)}[\log(1 - D(G(z)))]. \quad (3)$$

The discriminator aims to maximize its ability to distinguish between real training data images and those generated by the generator. In the loss function 3, minimizing $-\log(D(x))$ equates to maximizing the discriminator's probability. The generator, however, minimizes $\log(1 - D(G(z)))$ to generate images that can trick the discriminator. Training a GAN, being a two-player adversarial game, is complex and challenging.

When Goodfellow et al. [42] first proposed GANs, they were not capable of generating stylized images. As shown in Equation (3), the generator aims to minimize its cost to produce images similar to the real data. Building on the GAN framework, researchers developed image-to-image translation methods [66, 130, 170] to achieve style transfer. CycleGAN, proposed by Zhu et al. [170], transforms photos into paintings that closely resemble the styles of various artists using unpaired data. This method maps a source image data domain S to a target image domain T , learning the mapping $G : S \rightarrow T$. It employs an adversarial loss to distinguish between the data distribution of T and the distribution of images generated by $G(S)$.

Since the mapping $G : S \rightarrow T$ lacks constraints, another generator \tilde{G} is introduced for the reverse mapping $\tilde{G} : T \rightarrow S$ to ensure consistent results. Cycle consistency loss is added to enforce $\tilde{G}(G(S)) \approx S$. When G translates an image from S to T , \tilde{G} should be able to translate it back to S , ensuring the reconstructed image $\tilde{G}(G(S))$ closely matches the original image S . Similarly, for each image from T , the reverse should hold. For the mapping $G : S \rightarrow T$ and its discriminator D_T , the objective function is

$$\mathcal{L}_{\text{GAN}}(G, D_T, S, T) = \mathbb{E}_{t \sim p_{\text{data}}(t)}[\log D_T(t)] + \mathbb{E}_{s \sim p_{\text{data}}(s)}[\log(1 - D_T(G(s)))] \quad (4)$$

For each image s from the source image domain S , the image reconstruction cycle should be able to bring s back the original image—that is, $s \rightarrow G(s) \rightarrow \tilde{G}(G(s)) \approx s$. This gives the forward cycle consistency. However, for each image t from the target image domain T , G and \tilde{G} should also finish backward cycle consistency: $t \rightarrow \tilde{G}(t) \rightarrow G(\tilde{G}(t)) \approx t$. Therefore, we get the cycle consistency loss function written as follows:

$$\mathcal{L}_{\text{cyc}}(G, \tilde{G}) = \mathbb{E}_{s \sim p_{\text{data}}(s)}[\|\tilde{G}(G(s)) - s\|_1] + \mathbb{E}_{t \sim p_{\text{data}}(t)}[\|G(\tilde{G}(t)) - t\|_1]. \quad (5)$$

The whole loss function of CycleGAN is

$$\mathcal{L}(G, \tilde{G}, D_S, D_T) = \mathcal{L}_{\text{GAN}}(G, D_T, S, T) + \mathcal{L}_{\text{GAN}}(\tilde{G}, D_S, T, S) + \gamma \mathcal{L}_{\text{cyc}}(G, \tilde{G}). \quad (6)$$

CycleGAN allows the generation of stylized images that contain both the content of input images and the style of the training dataset, controlled by γ . It enriches diverse art styles for unpaired image datasets, enabling reconstructions like transforming a modern photo into a Monet or Van Gogh painting. As shown in Figure 3, CycleGAN's stylized results exhibit harmonious stylized characteristics, closely resembling Monet's style, compared to NST methods like AAMS [159], ASTSAN [110], and URUST [144], which contain varied features not truly reflective of Monet's style.

CycleGAN has drawbacks, such as unclear detailed contents. To improve image quality, AttentionGAN [132] incorporates the attention mechanism [140] into CycleGAN. AttentionGAN redesigns the second generator \tilde{G} to generate content and attention masks, fusing them with the generated image $G(s)$ to restore the source image s . This process is formulated as $\tilde{G}(G(s)) = C_s * A_s + G(s) * (1 - A_s)$. The term of \tilde{G} consists of an encoder \tilde{G}_E , an attention mask module \tilde{G}_A , and a content mask module \tilde{G}_C . \tilde{G}_C generates content masks, whereas \tilde{G}_A generates attention masks for both background and foreground. These masks are fused with $G(s)$ to restore s , formulated

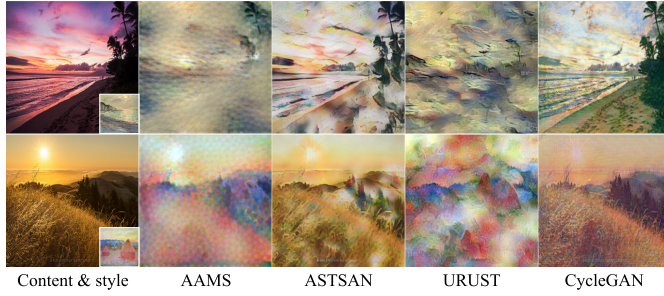


Fig. 3. Comparison of results. The first column displays content and style images. The last column shows CycleGAN’s output, whereas the others present results from various NST methods.

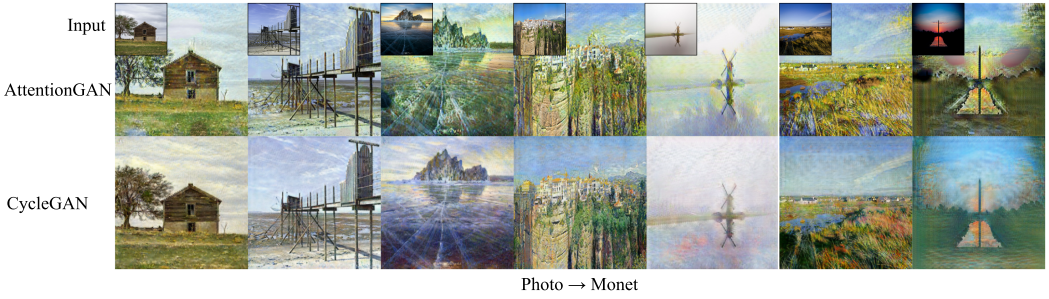


Fig. 4. Visual comparison between CycleGAN [170] and AttentionGAN [132].

as $\tilde{G}(G(s)) = \sum_{f=1}^{n-1} (C_s^f * A_s^f) + G(s) * A_s^b$, where the reconstructed image $\tilde{G}(G(s))$ should closely match the input source image s . Similarly, for a target image t , the cycle is formulated, and the reconstructed image should closely match t .

Figure 4 compares CycleGAN and AttentionGAN. The first row shows real photos (small images), and subsequent rows display style-reconstructed results. AttentionGAN generates images with more detailed content than CycleGAN, especially in photo-to-Monet transformations, due to its attention mask mechanism. Different datasets yield distinct styles, enabling diverse AI artwork. For instance, training CycleGAN with a photo-to-anime dataset transforms real photos into anime images. CartoonGAN [15] and MS-CartoonGAN [125] focus on reconstructing photos to anime, emphasizing sharp edges, smooth shading, and abstract textures. CartoonGAN’s edge-promoting adversarial loss is given by

$$\mathcal{L}_{\text{adv}}(G, D) = \mathbb{E}_{c_r \sim S_{\text{data}}(c_r)} [\log D(c_r)] + \mathbb{E}_{c_e \sim S_{\text{data}}(c_e)} [\log (1 - D(c_e))] + \mathbb{E}_{P_I \sim S_{\text{data}}(P_I)} [\log (1 - D(G(P_I)))] \quad (7)$$

The discriminator D maximizes the probability of distinguishing the generated image $G(P_I)$, cartoon images without sharp edges, and real cartoon images. CartoonGAN also introduces a content loss for smooth shading:

$$\mathcal{L}_{\text{con}}(G, D) = \mathbb{E}_{P_I \sim S_{\text{data}}(P_I)} [\|VGG_l(G(P_I)) - VGG_l(P_I)\|_1], \quad (8)$$

where l denotes a specific layer of VGG [126] for feature extraction. This loss uses ℓ_1 sparse regularization for better representation and regional characteristic preservation. Mimicking real art styles is crucial for AI artworks; however, diversity is also important. CycleGAN-based methods

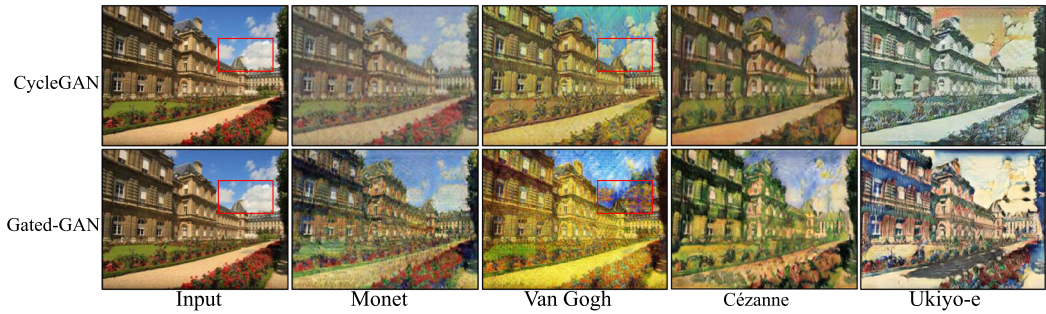


Fig. 5. Examples generated by Gated-GAN [14].

contribute to vivid art styles but generate only one style per model, which is inconvenient for diverse art style applications.

4.2.2 Per-Model Multi-Style. Gated-GAN, proposed by Chen et al. [14], enables the generation of multiple styles within a single framework. It uses an adversarial gated network, known as the gated transformer, for multi-collection style transfer. The model includes a switching trigger to select the desired style for the output. The gated transformer processes a set of photos $\{p_i\}_{i=1}^N \in P$ and multiple painting collections $Q = \{Q_1, Q_2, \dots, Q_K\}$, where K is the number of collections, each containing N_c images $\{q_i\}_{i=1}^{N_c}$. The network generates multiple styles $G(p, c)$ by applying the style of collection c to the input photo: $G(p, c) = Dec(T(Enc(p), c))$. Here, $T(\cdot)$ is a transformer built with residual networks, and $Enc(p)$ denotes the encoded feature space. Each style-specific branch in the transformer module contains additional parameters, minimizing the overall model complexity. Inspired by LabelGAN [135], Gated-GAN incorporates an auxiliary classifier to handle multiple style categories, optimizing the entropy to improve classification confidence. This design enables the model to generate diverse styles within a unified framework.

Despite its ability to produce multiple styles, Gated-GAN has limitations, such as occasionally lacking detailed content. Figure 5 shows examples generated by Gated-GAN, highlighting issues like the unnatural color block in the cloud region of the Van Gogh styled image.

Gated-GAN’s per-model multi-style approach contrasts with per-model-per-style methods like CycleGAN and CartoonGAN. Whereas CycleGAN and CartoonGAN generate one style per model, Gated-GAN supports multiple styles, enhancing versatility. However, models like AttentionGAN, which builds on CycleGAN, tend to produce higher-quality images with more detailed content. Gated-GAN’s strength lies in its ability to manage multiple styles efficiently, but it sometimes sacrifices detail. Combining the advantages of these approaches could lead to models that handle multiple styles and maintain high-quality, detailed outputs.

4.3 DM Method

Early research on DMs began with deep unsupervised learning using non-equilibrium thermodynamics [128] in 2015. However, the key breakthrough came with denoising diffusion probabilistic models [58]. Unlike other models, DMs generate images by gradually “sampling” from Gaussian noise, forming images through a series of steps.

DMs consist of two processes: the forward (diffusion) process and the reverse (denoising) process, both parameterized as Markov chains. The forward process adds Gaussian noise to the input image I_0 over T steps, transforming it into pure Gaussian noise Y_T . The reverse process denoises this to generate realistic images.

For real data $y_0 \sim q(y_0)$, the forward process is $q(y_t|y_{t-1}) = \mathcal{N}(y_t; \sqrt{1 - \beta_t}y_{t-1}, \beta_t\mathbf{I})$, where β_t is the variance at each step. The reverse process generates data using parameterized Gaussian distributions:

$$\begin{cases} p_\theta(y_0 : T) = p(y_T) \prod_{t=1}^T p_\theta(y_{t-1}|y_t), \\ p_\theta(y_{t-1}|y_t) = \mathcal{N}(y_{t-1}; \psi_\theta(y_t, t), \pi_\theta(y_t, t)), \end{cases} \quad (9)$$

where $p(y_T) = \mathcal{N}(y_T, \mathbf{0}, \mathbf{I})$ and $p_\theta(y_{t-1}|y_t)$ is the parameterized Gaussian distribution. The trained networks of $\psi_\theta(y_t, t)$ and $\pi_\theta(y_t, t)$ give the means and variances. The DM is to obtain the trained networks for the final-generation model. The objective function of denoising score matching, integrating score matching [65] and denoising principles [141], is $\mathbb{E}_{y \sim p(y)} \mathbb{E}_{\tilde{y} \sim q(\tilde{y}|y)} [\|s_\theta(\tilde{y}) - \Delta_{\tilde{y}} \log q(\tilde{y}|y)\|_2^2]$, where s_θ (Stein score) is the real noisy data. For Gaussian noise, this simplifies to

$$\sum_{\epsilon \in B} \lambda(\epsilon) \mathbb{E}_{y \sim p(y)} \mathbb{E}_{\tilde{y} \sim \mathcal{N}(y, \epsilon)} \left[\left\| s_\theta(\tilde{y}, \epsilon) - \frac{\tilde{y} - y}{\epsilon^2} \right\| \right], \quad (10)$$

where B is the set of standard deviations and $\lambda(\epsilon)$ is a coefficient function. Using Langevin dynamics principles, the iterative update is $y_k \leftarrow y_{k-1} + \varphi \Delta_y \log p(y_{k-1}) + \sqrt{2\varphi} z_k$, $1 \leq k \leq K$. This method allows the gradual transformation of noise into the desired data. Ho et al. [58] proposed an objective function for optimization based on variational bounds, leading to $\mathbb{E}_{t, \xi} [C \|\xi - \xi_\theta(\sqrt{\delta_t}y_0 + \sqrt{1 - \delta_t}\xi, t)\|_2^2]$, where C is a definite constant, ξ is the noise generated randomly from a standard Gaussian distribution, and δ is also a constant changing with t . Let $\beta_t \sim \mathcal{N}(0, 1)$, $\delta = 1 - \beta_t$, $\delta_t = \prod_{i=1}^t \delta_i$, where we can set $\beta_t = 0.5$.

Compared to GANs, DMs offer significant advantages in stability and simplicity. Whereas GANs require training both a generator and discriminator, DMs focus solely on the generator with a straightforward Gaussian-based loss, avoiding the adversarial nature that often causes instability in GANs. Dhariwal and Nichol [28] demonstrated that DMs outperform GANs in image quality, achieving lower FID (Fréchet Inception Distance) scores across multiple resolutions on ImageNet. This indicates superior fidelity and diversity in generated samples.

DMs benefit from simpler training processes and avoid issues like mode collapse common in GANs. Additionally, classifier guidance in DMs effectively balances diversity and fidelity, further enhancing image quality. These features make DMs more computationally efficient and easier to optimize, marking a significant advance in generative modeling and image synthesis.

In summary, DMs streamline the training process, reduce computational complexity, and achieve superior performance compared to GANs. The success of DMs lies in their ability to mimic a straightforward reverse process, fitting simple Gaussian distributions, which significantly enhances optimization and performance.

4.4 Art-Style-Reconstruction Algorithm

For comparison fairness, we classify the AI artworks into style transfer and style reconstruction. Meanwhile, we take the methodology and the art style to consider. This section analyzes different method algorithms under one art style.

4.4.1 Line Drawings. As NST methods achieve sketching directly from images (e.g., APDrawingGAN [161], synthesizing human-like sketches [74]), we analyze line-drawing methods focusing on the drawing process.

Ha and Eck [47] proposed sketch-rnn, an RNN capable of generating stroke-based drawings. A sketch is defined as a point list, where each point is a vector with five elements: $(\Delta x, \Delta y, st_1, st_2, st_3)$. The sketch-rnn model employs a sequence-to-sequence VAE architecture, similar to those in other works [78, 121]. It encodes a sketch image into a latent vector and decodes it stroke by stroke, guided by the encoded states.

The encoding process involves two RNNs processing the sketch sequence and its reverse, resulting in final hidden states \underline{h} and \overleftarrow{h} , combined into h_s . The process can be written as follows:

$$\underline{h} = \overrightarrow{\text{encode}}(Sq), \overleftarrow{h} = \overleftarrow{\text{encode}}(Sq_{reverse}), h_s = [\underline{h}; \overleftarrow{h}]. \quad (11)$$

The sketch-rnn encoder processes the concatenated hidden states h_s into δ and $\hat{\eta}$ of size V_z . $\hat{\eta}$ is transformed into the non-negative standard deviation η via exponentiation. Using δ , η , $\mathcal{N}(0, 1)$, and a vector of 2D Gaussian variables, a random latent vector $z \in \mathbb{R}^{V_z}$ is constructed, akin to the VAE approach in the work of Kingma and Welling [78]. z is conditioned on the input sketch, differing from deterministic outputs.

The auto-regressive RNN decoder of sketch-rnn sequentially predicts strokes using the last point, previous sketch sequence Sq_{di-1} , and latent vector z . It iterates through drawing steps to generate simple object sketches and can produce ablation sketches by adjusting the Kullback-Leibler loss weight. However, sketch-rnn struggles with complex images and supports limited sketch styles, allowing human participation only in predicting unfinished sketches.

The Creative Sketch Generation method [41] introduces DoodlerGAN, which leverages StyleGAN2 [41] to sequentially generate sketch parts guided by human observations. Its part selector facilitates a human-in-the-loop sketching process but is currently limited to birds and creative creatures.

An alternative approach [169] uses reinforcement learning (Deep Q-learning) in Doodle-SDQ to train an agent to draw strokes on a virtual canvas, aiming to reconstruct a reference image stroke by stroke. The similarity metric \mathbb{S}_k evaluates the canvas's closeness to the input image: $\mathbb{S}_k = \frac{\sum_{i=1}^L \sum_{j=1}^L (P_{ij}^k - P_{ij}^{\text{ref}})^2}{L^2}$, where P_{ij}^k and P_{ij}^{ref} are pixel values at position (i, j) on the canvas and input image, respectively, at step k . The pixel reward $R_p = \mathbb{S}_k - \mathbb{S}_{k+1}$ optimizes the executing action at each step.

Doodle-SDQ's line-stroke sketching penalizes slow movements (P_s for <5 pixels/step or pen lift) and incorrect color choices (P_c with β adjusted for grayscale/color input). The final reward $R_k = R_p + P_s + \beta P_c$ combines pixel similarity and penalties. Although Doodle-SDQ reproduces reference sketches well, it cannot sketch from real photos and lacks artistic creativity. In the work of Zhou et al. [169], strokes are simulated by a virtual 'pen,' with reinforcement learning mapping actions to strokes. This inspires the development of diverse stroke types, potentially mimicking oil paintings and ink wash paintings.

4.4.2 Oil Painting. The method in the work of Huang et al. [64] utilizes a model-based DDPG (deep deterministic policy gradient) [91] algorithm to simulate a stroke-by-stroke oil-painting process. Bézier curves mimic brushstroke paths, and a circle represents the brush tip. The control points of the Bézier curves serve as actions, enabling action-to-stroke mapping. Given an input photo P_I and an initial canvas C_0 , the model generates an action sequence $(b_0; b_1, \dots, b_{n-1})$ to sequentially render strokes onto the canvas, producing the final painting C_N . This task is formulated as a Markov decision process with a state space \mathfrak{S} , action space \mathfrak{B} , transition function $\text{trans}(s_n, b_n)$, and reward function $R(s_n, b_n)$ designed to minimize the distance between the input image and the canvas at each step: $R(s_n, b_n) = L_n - L_{n+1}$, where L_n and L_{n+1} represent the losses between P_I and the current/next canvases, respectively. The model aims to maximize the accumulated discounted future reward $R_n = \sum_{i=n}^T \epsilon^{(i-n)} R(s_i, b_i)$ with a discount factor $\epsilon \in (0, 1)$.

The original DDPG algorithm is composed of an actor network $\Phi(s)$ that maps state s_n to actions b_n and a critic network $\Psi(s, b)$ that estimates reward to guide the actor. Both networks are trained using the Bellman equation (12), with an experienced replay buffer storing the latest 800 episodes to enhance data usage:

$$\Psi(s_n, b_n) = R(s_n, b_n) + \epsilon \Psi(s_{n+1}, \Phi(s_{n+1})). \quad (12)$$

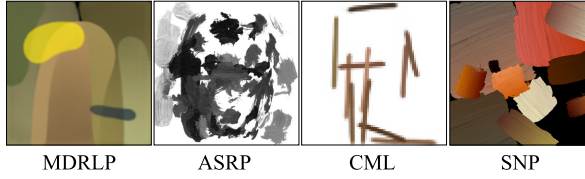


Fig. 6. Stroke comparison. The images, from left to right, are generated by MDRLP [64], ASRP [7], CML [123], and SNP [171], respectively.

The **MDRL Painter (MDRLP)** method in the work of Huang et al. [64] improves upon line drawing approaches by simulating oil-painting brushstrokes using Bézier curves and circles. This method is improved from the line-drawing method of Zhou et al. [169] by designing the brushstroke. Although it can create paintings from various input images, the details are coarse, and the simulated stroke textures lack realism compared to human-made oil paintings.

The **Artistic Style in Robotic Painting (ASRP)** approach of Bidgoli et al. [7] aimed to mimic human artist styles by generating brushstroke samples with similar textures. It uses Bézier curves to simulate strokes without tuning transparency, ensuring realism. VAEs were trained to capture artist brushstroke features, resulting in stroke textures close to those of human artists, but the final paintings lacked content detail.

Schaldenbrand and Oh [123] improved painting quality by proposing CML, a reinforcement learning model based on the work of Huang et al. [64]. CML emphasizes salient regions using VGG-16 features and ℓ_2 distance, mimicking the human painting process. However, even though the model captures the painting process well, it loses detailed content and stroke texture clarity.

Another AI oil-painting model, **Stylized Neural Painting (SNP)** by Zou et al. [171], contributes to stroke modeling by generating strokes with realistic oil-painting textures. A dual-pathway neural network independently generates stroke colors and textures. The model predicts and renders strokes step by step to optimize the final canvas C_N to resemble the input image I_r : $C_N = \phi_{n=1 \sim N}(\tilde{s}) \approx I_r$, where $\phi_{n=1 \sim N}(\cdot)$ maps stroke parameters to canvas states. The model optimizes stroke parameters $\tilde{s} = [s_1, \dots, s_N]$ using gradient descent to minimize the visual similarity loss $\mathcal{L}(C_N, I_r)$: $\tilde{s} \leftarrow \tilde{s} - \theta \frac{\partial \mathcal{L}(C_N, I_r)}{\partial \tilde{s}}$, where θ is the learning rate.

The SNP method [171] produces paintings with more details and realistic oil-painting stroke textures compared to other works [7, 64, 123], as shown in Figure 6. ASRP [7] and SNP exhibit clear oil-painting textures; however, SNP's output size is fixed, requiring input images with the same aspect ratio. This can distort non-conforming images, and some input details may become blurry. Additionally, SNP requires more computation time than MDRLP.

4.4.3 Ink Wash Painting. Ink wash painting seems difficult to achieve with learning-based methods, and there are only a few research studies on the topic [151, 152]. For example, the texture of Chinese hair brush is difficult to mimic, although conventional SBR methods make contributions [131] to stroke modelling. Xie et al. [151] proposed using the Markov decision process to imitate drawing a stroke. The authors first used a tip V and a circle with center C_o and radius r_o to model the brush agent. The Markov decision process consists of a tuple $(\hat{S}, \hat{\mathcal{A}}, P_d, P_T, \phi)$, where \hat{S} is a set of continuous states of the canvas, $\hat{\mathcal{A}}$ is a set of continuous actions, and P_d is the probability density of the initial state. $P_T(\hat{s}'|\hat{s}, \hat{a})$ is the transition of the probability density from the current state of the canvas $\hat{s} \in \hat{S}$ to the next state $\hat{s}' \in \hat{S}$ when taking action $\hat{a} \in \hat{\mathcal{A}}$. The term $\phi(\hat{s}, \hat{a}, \hat{s}')$ denotes the immediate reward for the transition from \hat{s} to \hat{s}' . Let $\mathcal{T} = (\hat{s}_1, \hat{a}_1, \hat{s}_L, \hat{a}_L, \hat{s}_{L+1})$ be a trajectory of length L . Then, the return (i.e., the sum of the accumulating discounted future rewards) along \mathcal{T} is written as $\phi(\mathcal{T}) = \sum_{l=1}^L \sigma^{L-l} \phi(\hat{s}_l, \hat{a}_l, \hat{s}_{l+1})$, where $\sigma \in [0, 1)$ is the discount

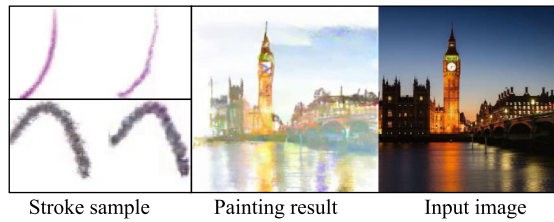


Fig. 7. The pastel-like stroke samples and the painting result generated by the method of NP [109].

value for the future reward. Meanwhile, the authors designed four actions to move the brush agent, and in the reinforcement learning model, the brush agent was trained to generate hair brushstrokes.

Since the algorithm achieves high fidelity of hair brushstroke textures, the reinforcement learning model is, at last, able to use the brush agent to generate ink wash paintings or Chinese paintings. Although the painting results contain textures of hair brushstrokes and characteristics of ink wash paintings, the method does not provide the painting process. Therefore, we do not know what happened during the painting procedure. We are not sure if the paintings are painted stroke by stroke. Moreover, the method description does not explain how the painting agent processes the input reference images and how the agent decomposes the images into strokes.

4.4.4 Pastel-Like Painting. The method of **Neural Painters (NP)** in the work of Nakano [109] uses the GAN-based model and VAE-based model to simulate an intrinsic style-transform painting. Since the stroke textures are close to the pastel-painting style, we have called this form of painting *pastel-like painting*. However, the finished paintings express few characteristics of pastel paintings. The GAN-based and VAE-based models in the method were used to generate pastel-like strokes by training the models on the stroke dataset provided by the MyPaint program. When training the GAN- and VAE-based models, Nakano [109] labeled the dataset for the action space mapping a single action to a single brushstroke. The entire model (a neural painter) then used the GAN- or VAE-based model to generate pastel-like strokes rendering on the canvas. By dividing the canvas into grids with the same size as the stroke image generated by the GAN- or VAE-base model, the neural painter was able to recreate a pastel-like painting based on the given image. However, the paintings generated by NP lost much detailed content and the pastel-painting stroke textures were not clear. As Figure 7 shows, with images from Nakano [109], the stroke samples contained characteristics of pastel-painting stroke textures, but the painting not only lost too much detailed content but also had few pastel-painting characteristics.

4.4.5 Robotic Painting. Robotic painting has long captivated both artists and robotics experts. Most artistic painting robots use acrylic paints [75], which are nearly as versatile as oil paints but are water soluble, eliminating the need for harsh or toxic thinners and solvents. An example of an acrylic painting robot is the e-David robot [43, 92, 93], developed by Oliver Dessoir, Thomas Lindmeier, Mark Tautzenberger, and Sören Pirk. This system comprises an industrial robot equipped with a paintbrush and a visual feedback system, utilizing a set of pre-mixed colors. Additional color mixing is achieved by applying translucent brushstrokes to the canvas, considering the Kubelka-Munk paint film theory. The e-David robot can also learn to replicate brushstrokes through trial and error. The LETI painting robot [75] introduces a new type of robot capable of precisely metering and mixing acrylic paints, demonstrating high-quality painting results. The robotic system's capabilities are showcased through four artworks: replicas of landscapes by Claude Monet and Arkhip Kuindzhi, and synthetic images generated by StyleGAN2 and Midjourney neural networks.

These results can be applied to computer-generated creativity, art replication and restoration, and color 3D printing.

The work by Bidgoli et al. [7] presents a new approach that integrates artistic style into the process of robotic painting through collaboration with human artists. The method involves collecting brushstroke samples from artists, training a generative model to imitate the artist's style, and then fine-tuning the brushstroke rendering model to adapt it to robotic painting. Their user studies have shown that this method can effectively apply the artist's style to robotic painting. The use of a VMS (Visual Measurement System) and an RPS (Robotic Painting System) to simulate brushstrokes is presented by Guo et al. [44]. The specific method involves using VMS to capture the interaction trajectories and environmental state information during the artist's painting process. Then, RPS mimics human painting actions based on this information, utilizing real-time visual feedback to adjust the robot's movements, thus achieving precise brushstroke simulation. Through these methods, the proposed ShadowPainter system can simulate brushstroke effects that are close to human levels.

Work Mikalonyté and Kneer [106] explores whether AI-driven robots can be regarded as artists and create real works of art. Two experiments were conducted to investigate people's perception of the artistic quality of robot paintings and their acceptance of the identity of robot artists. Experimental results show that although people generally believe that robot paintings are not much different from human works in terms of artistic quality, they have reservations about identifying robots as artists.

In conclusion, robotic painting has become a fascinating field that bridges art and technology. Various systems and methods have been developed to mimic and even surpass human artistic abilities. From using acrylic paints to precise metering and mixing techniques, these robots have demonstrated extraordinary painting capability. The integration of artistic styles through human-machine collaboration further enhances the creative possibilities of robotic painting. As technology advances, we can expect more innovative and captivating artworks to emerge from this exciting field, breaking the boundaries of traditional art forms and opening new avenues for artistic expression. However, the debate over whether AI-driven robots can truly be considered artists remains unresolved. Despite the increasing technical proficiency and artistic quality approaching human standards, societal acceptance of robots as genuine creators of art continues to lag. Future research and development in this field may focus on bridging this gap, enhancing the creative capabilities of robots, and addressing the ethical and philosophical issues surrounding AI and art.

5 Evaluation

From the SBR methods of the early 1990s to increasingly learning-based methods of drawing/painting and generating for image processing, research into AI painting has reached a new pinnacle. We have analyzed recent methods based on the taxonomy of generation methods and art styles. Different models and algorithms have been proposed to achieve diverse kinds of creative artwork. Although these methods are rich in AI artworks, their drawbacks are still obvious as well as their advantages. The discussion about the evaluation of aesthetics and usability catches much attention of researchers in both industry and academia.

We propose that AI artworks should be compared within the same field or category. However, for existing evaluations of methods and the artworks generated by these methods, there are no uniform standards. Some evaluation aspects do not fit certain methods or artworks. For example, we should not take the details of the content in artwork into account only when comparing the method and its outputs. We are comparing artworks instead of the high resolution of an image: we should be taking the art elements into account.

5.1 Evaluation Metrics

Currently, there are four principal representative metrics widely used for image quality evaluation, namely IS (Inception Score, FID, CLIP (Contrastive Language-Image Pre-training), and GIQA (Generated Image Quality Assessment) [143]. IS evaluates the effectiveness of generative models, mainly measuring the quality and diversity of generated images. It assesses the classification effectiveness of generated images based on the image classifier Inception v3. FID evaluates the effectiveness of generative models, measuring the distance between the distribution of generated images and the distribution of real images. FID calculates the difference between these two distributions based on the Inception network. CLIP is an artificial intelligence model developed by OpenAI that can simultaneously understand text and images. It is not just an evaluation metric but also a bridge connecting language and visual information. GIQA evaluates the quality of generated images, defining “quality” as the similarity between the distribution of generated images and real datasets. This metric can score individual-generated images, which is a capability that some previous generative model evaluation metrics lacked.

These four metrics cannot be directly compared due to their different calculation methods and result ranges. Moreover, none of these evaluation metrics target elements related to artistic aesthetics. When image evaluation is needed from the perspective of the image or artwork itself, these evaluation metrics are not very applicable. To this end, we propose a six-dimensional evaluation index to focus on evaluating images from an artistic aesthetic perspective, which perfectly fills this gap.

We have referred to some elements used for evaluation from the artistic field. Art vocabulary [134] describes the elements of art and principle of design as follows:

- *The elements of art*: Form, line, shape, space, texture, and color. Color is light reflected off objects. There are three main characteristics: hue (the name of the color: red, green, blue, etc.), value (how light or dark it is), and intensity (how bright or dull it is).
- *The principles of design*: Balance, movement, emphasis, repetition, proportion, pattern, rhythm, unity, and variety.

When evaluating AI-generated images, we cannot only consider the quality of the generated images, namely just using the four evaluation metrics mentioned earlier. From an artistic perspective, we should evaluate the artistic characteristics of the works. Thus, we design several items of the evaluation for AI artworks inspired by the AI criticism [37], exploring the representativity of art paintings [22], beauty in abstract paintings [102], aesthetic-aware image style transfer [61], and aesthetics-guided graph clustering [165]. We mainly design the items on two aspects, the *beauty* of the entire painting and the *art elements*. In particular, the beauty of the painting takes 50% of the score, and the elements too. The art elements are *line smooth*, *stroke texture*, *colors*, *contents*, and *art style* recognizability. As Table 1 indicates, the beauty of the entire artwork is the core characteristic of artwork, so the item of beauty takes 50% of an artwork. Each of the other elements takes 10% of an artwork. We ask the participants to score the paintings on the beauty of the entire artwork and all elements according to a 5-point Likert scale [90] (the points being strongly good (5), good (4), neither good nor bad (3), bad (2), and strongly bad (1)). The questions are as follows:

- How beautiful is this artwork?
- How well are lines expressed in this artwork?
- How well are stroke textures expressed in this artwork?
- How well is the light and shade of the color treated in this artwork?
- How detailed are the contents contained in this artwork?
- How easy is it to recognize the art style of this artwork?

Table 1. Evaluation Items Used in the User Study

Item	Explanation
Beauty	The aesthetic evaluation of the entire artwork
Line	The expression and smoothness of the lines in the artwork
Texture	The stroke texture expressed in the artwork
Color	The treatment of light and shade in the artwork
Contents	The features of the whole artwork, including the details
Style	The art style of the artwork—for example, oil-painting style



Fig. 8. Visual comparison of existing NST methods. The first column shows the content and style images (the small images). The second through fourth columns contain the results of AAMS [159], ASTSAN [110], and URUST [144], respectively.

5.2 Experiments and Analysis

Experiments were conducted using the the methods described on the same platform with the authors providing codes and pre-trained models. We then choose the best results of the compared methods as the test images for visual comparison and user study.

5.2.1 Visual Comparison. We first compare the results generated by the methods of image style transfer. In particular, the stylized images are synthesized by the content image and the style image. Figure 8 shows the sample results generated by methods of AAMS [159], ASTSAN [110], and URUST [144]. The first column contains the content images and style images (small). The remaining columns, from left to right, are the generated images of AAMS [159], ASTSAN [110], and URUST [144], respectively. All of the results present the style features well.

However, as can be seen from the top row (see Figure 8), the style image is a pencil drawing in the top row. Yet, the image generated by ASTSAN [110] still retains the original color features of the content image, indicating incomplete style transfer. Although the image generated by URUST [144] exhibits pencil drawing features, the content of the bird is blurred, indicating imperfect content expression. The image generated by AAMS [159] presents clear content of the target image, and the style features are also harmoniously synthesized into the target image. From a visual aesthetic perspective, considering overall aesthetic *beauty*, *lines*, *colors*, *content* details,

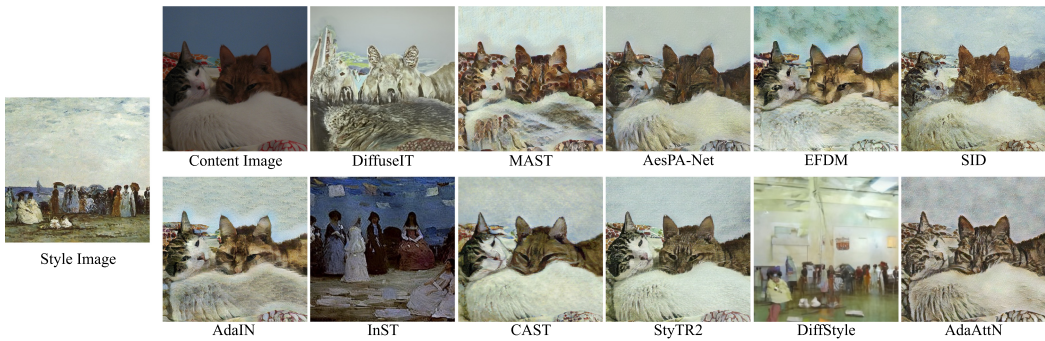


Fig. 9. Visual comparison of existing style transfer methods. The image at left is the style image, and the first image in the top row is the content image. The compared images refer to the work of SID (Style Injection in Diffusion) [21]. The methods are DiffuseIT [80], MAST [24], AesPA-Net [60], EFDM [167], SID [21], AdaIN [63], InST [166], CAST [168], StyTR2 [23], DiffStyle [67], and AdaAttN [95].

and *style*, the image generated by AAMS [159] appears more aesthetically pleasing than the others. Therefore, we conclude that the results of image style transfer should contain detailed content of the target image, and the features of the style image should not overshadow the content image.

Figure 9 shows the visual results of new style transfer methods. The visual effects of the images generated by AesPA-Net [60], EFDM [167], AdaIN [63], CAST [168], StyTR2 [23], and AdaAttN [95] are quite impressive. They maintain high clarity and content detail, with good color reproduction and contrast. The stroke and line textures are also well presented. The cat's image is vivid, and the background environments have their own characteristics, showcasing different artistic styles. However, in terms of style transfer, they do not fully embody the features of the style image, so they are not the best in this aspect.

The images generated by MAST [24] and SID (Style Injection in Diffusion) [21] are slightly inferior in content detail. Although they basically capture the cat's image and background environment, they are slightly lacking in clarity, color reproduction, and contrast. Some details may be blurry, and the colors may be somewhat distorted, affecting the overall visual effect. The line sense and stroke texture are not very obvious. The content detail expression in images generated by DiffuseIT [80], InST [166], and DiffStyle [67] is very poor. For InST [166] and DiffStyle [67], the cat's image is almost indistinguishable. On the contrary, InST [166] expresses more content from the style image. Although it is hard to recognize the content of the image generated by DiffStyle [67], its overall color expression creates a fresh and 'cute' effect.

In summary, the evaluation of style transfer results across various models highlights several key features necessary for generating high-quality, new-style artistic images. From the perspective of *beauty*, an ideal artistic image should exhibit a balanced composition of visually pleasing elements, including harmonious color schemes and well-composed subjects. Regarding *lines*, clarity and sharpness are crucial for defining objects and subjects, contributing to the overall structural readability of the image. In terms of *colors*, accurate color reproduction and contrast are essential for enhancing visual appeal and reflecting the desired mood and atmosphere. *Stroke texture* plays a vital role in conveying the sense of artistic technique and traditional medium, providing a tactile experience for the viewer. *Content* details are important for maintaining the recognizability and realism of the main subject, ensuring that key elements are neither lost nor distorted during the transformation process. Finally, the *style* itself must be faithfully reproduced, capturing the unique characteristics and nuances of the reference style image. Balancing these elements ensures that the



Fig. 10. Visual comparison of existing GAN-based methods for photo-to-cartoon. The first column shows the input images, and the remaining columns from left to right are generated images by methods of GANs N' Roses [20], U-GAT-IT [77], and WBC [147], respectively.

generated artistic image not only adheres to the desired style but also stands out as a cohesive and aesthetically engaging piece of art.

Figure 10 shows the results generated by style transfer methods. Note that the style of the generated images is learned from the training dataset, not synthesized from a style image. The first column shows the input images, and the remaining columns, from left to right, are generated images by GANs N' Roses [20], U-GAT-IT [77], and WBC [147], respectively. The first row input image is from the dataset provided by U-GAT-IT [77], and the last input image is from the sample image test provided by WBC [147]. When comparing the first three rows of images, we observe that images generated by WBC [147] retain more realistic contents of the input images than the others. The images generated by GANs N' Roses [20] and U-GAT-IT [77] present more non-realistic cartoon features than WBC [147]. However, when comparing the bottom row images, we observe that the image generated by U-GAT-IT [77] has few cartoon features but blurred contents. Based on the analysis, we conclude that U-GAT-IT [77] has a low generalization.

Figure 11 shows the results generated by line drawings methods. The top row shows the input reference images (small images), and the rest of the rows, from top to bottom, show the results generated by photo-sketching [85] and APDrawingGAN [161], respectively. The images generated by photo-sketching [85] lose so much content that it is difficult to recognize the object in the image. Although results generated by APDrawingGAN [161] contain sufficient image content, the expression of the girl's hair is not satisfactory.

Figure 12 shows another line drawing results generated by DoodlerGAN [41]. The images are created by the online demo provided by the authors. The model only creates birds or bird-like creatures. The images are generated step by step. The whole image consists of several components of a bird or bird-like creatures. The human or the computer draws a final step in the process to finish a component. Figure 12(a) and (c) are finished by the cooperation of a human and a computer. Figure 12(b) and (d) are generated by the computer only. We observe that all images are like birds but not real birds.

Figure 13 shows the results generated by methods of painting. The results are created stroke by stroke. The left column shows the input images, and the remaining columns from left to right are the results generated by methods of MDRLP [64], SNP [171], Stroke-GAN Painter [145], and NP [109], respectively. The images in the three middle columns have colors closer to the input

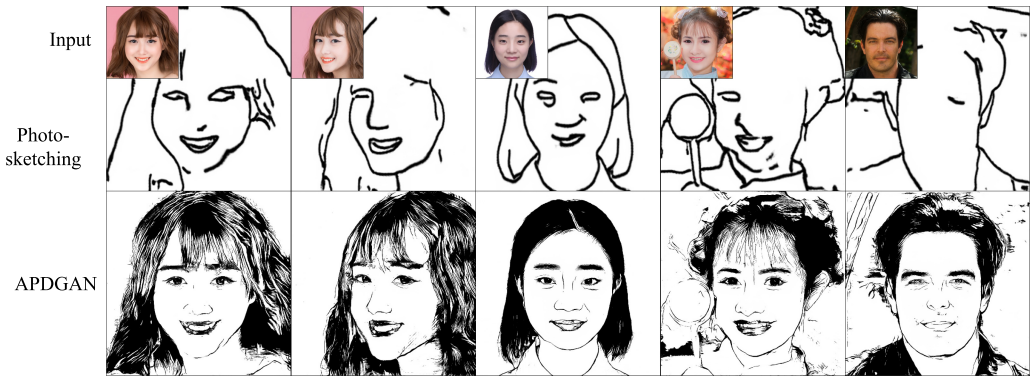


Fig. 11. Visual comparison for photo-to-sketch. The top row shows the reference images. The middle row shows the results of the photo-sketching method [85], and the last row shows the results of the APDrawing-GAN method (APDGAN) [161].

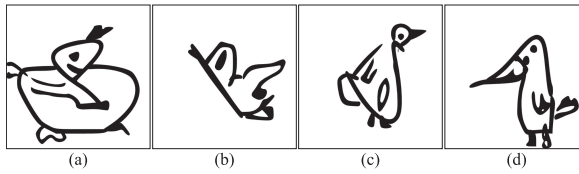


Fig. 12. Line drawings generated by DoodlerGAN [41].

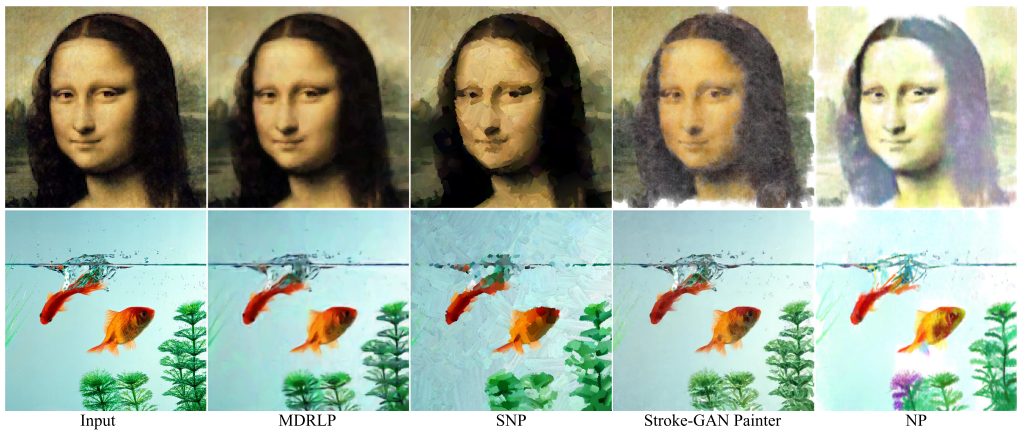


Fig. 13. Visual comparison for paintings. The left column contains the input reference images. The other columns are the painting results of different methods. The three middle-column methods use oil-painting strokes to create paintings. The right column uses pastel-like strokes to generate paintings.

images than the right-column images. Images generated by SNP [171] present clearer stroke textures than others. Images generated by MDRLP [64] contain more details than others. Images generated by MDRLP [64], Stroke-GAN Painter [145], and SNP [171] look like oil painting, especially the brushstroke texture of SNP [171]. The style of images generated by NP [109] is difficult to recognize since the stroke texture is more like pastel painting than oil painting, but the art style is close to watercolor painting.

Table 2. ICC Results of the Step 1 Test

Two-Way Mixed/Random Consistency	ICC	95% CI
Single measure ICC (C,1)	0.437	0.373 ~ 0.513
Average measure ICC (C,K)	0.985	0.980 ~ 0.989

Table 3. ICC Results of the Step 2 Test

Two-Way Mixed/Random Consistency	ICC	95% CI
Single measure ICC (C,1)	0.498	0.432 ~ 0.574
Average measure ICC (C,K)	0.988	0.985 ~ 0.991

5.2.2 *User Study.* To make an objective evaluation of the generated images, we undertake a two-step user study. For a fair comparison, we conduct a blind-trial test among the participants. The participants know neither the authors of the methods used for generating comparison paintings nor the experimenter. The participants are chosen from various backgrounds (69.2% in the art field, and 85.1% know about AI art), age groups (18–60 years), and genders (74 females and 127 males).

We designed the user study as a two-step test for the six-dimensional evaluation index analysis to find suitable items for a certain art style, inspired by the work of Tong et al. [136]. For the first step, we mix all the painting results in the same questionnaire and then ask the participants to score all the paintings according to the six evaluation items. In the second step, we classify the paintings into two categories: style-transform paintings and style-reconstruction paintings (stroke-by-stroke paintings). The style-reconstruction paintings contain the painting process images, and the paintings with the same style are put in the same group. We then ask the participants to score the paintings based on a 5-point Likert scale [90]. The participants finish the user study's Step 1 and Step 2.

Tables 2 and 3 show the **Intraclass Correlation Coefficient (ICC)** results of the two-step user study. In analyzing two sets of ICC data, we observed similar trends regarding the reliability of single and average measurements. In both datasets, the single measure ICC (C,1) values, 0.437 and 0.498 respectively, indicate a certain to moderate degree of correlation in single measurements, but not particularly strong. The 95% CIs (confidence intervals) for these single measures show a range of fluctuation, suggesting room for improvement and reflecting the potential impact of random errors or individual differences. However, the average measure ICC (C,K) values exhibit extremely high reliability in both sets, reaching 0.985 and 0.988. The narrow CIs further confirm that averaging multiple measurements significantly enhances measurement accuracy and consistency. These findings underscore the importance of repeated measurements in improving data quality and reliability. In the subsequent data analysis, we mainly took the average score of each question for further analysis.

Table 4 shows the experimental results of Step 1, and Table 5 shows the results of Step 2. Scores in the two tables are marked with different colors for observation. Red indicates the highest scores, blue indicates the lowest scores, and orange represents scores lower than 3 except blue ones.

Table 4 shows the six-dimensional evaluation index scores on mixed artworks. In the beauty column of Table 4, we observe that the results generated by the method of photo-sketching [85] give the lowest scores (2.849). Compared with other paintings, the sketches generated by photo-sketching [85] have little content from the input image, and we cannot readily recognize what the sketches express in some cases (as Figure 11 shows). The score is 2.849, which means that most participants judged the sketches to be poor in terms of beauty. The sketches generated by DoodlerGAN [41] also obtain a lower score (3.000) compared with other paintings. However, when comparing the line smoothness of the paintings, we observe that paintings generated by the method of

Table 4. Scores on Evaluation Items in the User Study, Step 1

Methods	Beauty (50%)	Line (10%)	Texture (10%)	Color (10%)	Content (10%)	Style (10%)	Mixed Total
AAMS [159]	3.756	3.532	3.582	3.677	3.587	3.613	3.677
ASTSAN [110]	3.095	2.935	3.069	3.069	3.000	3.185	3.073
URUST [144]	3.164	3.000	3.224	3.086	3.125	3.267	3.152
SID [21]	3.741	3.444	3.504	3.478	3.483	3.586	3.620
AesPA-Net [60]	3.836	3.612	3.716	3.556	3.746	3.716	3.753
CAST [168]	3.625	3.444	3.608	3.526	3.483	3.539	3.572
StyTR2 [23]	3.884	3.591	3.711	3.591	3.716	3.651	3.768
EFDM [167]	3.595	3.323	3.341	3.418	3.487	3.448	3.499
MAST [24]	3.108	3.004	2.918	2.996	3.116	3.065	3.064
AdaAttN [95]	3.582	3.358	3.371	3.293	3.379	3.362	3.467
AdaIN [63]	3.685	3.405	3.565	3.466	3.440	3.539	3.584
DiffuseIT [80]	3.233	2.978	3.185	3.082	3.065	3.151	3.163
InST [166]	3.496	3.216	3.353	3.233	3.341	3.388	3.401
DiffStyle [67]	3.246	2.892	3.125	2.978	3.121	3.043	3.139
CycleGAN [170]	3.543	3.188	3.338	3.297	3.358	3.345	3.424
Gated-GAN [14]	3.853	3.491	3.591	3.690	3.634	3.763	3.744
StarGAN [18]	3.353	3.168	3.250	3.134	3.297	3.254	3.287
StarGAN v2 [19]	3.366	3.134	3.190	3.095	3.233	3.216	3.270
H-SRC [72]	2.961	2.845	2.901	2.884	2.836	2.940	2.921
MSC [10]	3.522	3.203	3.280	3.306	3.315	3.224	3.394
U-GAT-IT [77]	3.670	3.391	3.460	3.432	3.485	3.460	3.558
WBC [147]	3.432	3.263	3.319	3.235	3.310	3.262	3.355
CartoonGAN [15]	3.358	3.172	3.315	3.284	3.263	3.280	3.310
MSCartoonGAN [125]	3.457	3.272	3.379	3.241	3.366	3.379	3.392
GANs N' Roses [20]	3.865	3.553	3.585	3.586	3.658	3.726	3.743
LGLD [13]	3.862	3.625	3.595	3.366	3.603	3.828	3.733
APDrawingGAN++ [162]	3.565	3.504	3.582	3.220	3.526	3.608	3.526
APDrawingGAN [161]	3.875	3.694	3.642	3.302	3.612	3.741	3.728
Photo-sketching [85]	2.849	2.784	2.845	2.828	2.853	3.194	2.875
DoodlerGAN [41]	3.000	3.022	2.970	2.918	2.927	3.263	3.010
NP [109]	3.427	3.190	3.310	3.241	3.379	3.397	3.365
MDRLP [64]	3.534	3.310	3.418	3.448	3.418	3.474	3.474
SNP [171]	3.659	3.392	3.491	3.547	3.445	3.582	3.576
Stroke-GAN Painter [145]	3.613	3.430	3.516	3.521	3.456	3.453	3.544
PaintTransformer [94]	3.621	3.512	3.447	3.342	3.452	3.567	3.543
Intelli-paint [127]	3.653	3.521	3.522	3.601	3.485	3.587	3.598
Im2Oil [137]	3.732	3.311	3.554	3.663	3.512	3.601	3.630
RST [79]	3.712	3.344	3.558	3.628	3.523	3.612	3.623
PST [98]	4.112	3.603	3.823	3.892	3.884	3.974	3.983
Average	3.529	3.299	3.389	3.337	3.383	3.443	3.450

Note: All painting results are put in the same questionnaire.

Table 5. Scores on Evaluation Items in the User Study, Step 2

Category	Methods	Beauty (50%)	Line (10%)	Texture (10%)	Color (10%)	Content (10%)	Style (10%)	Categorized Total
Style Transfer/ Transform New Style	AAMS [159]	3.910	3.637	3.672	3.706	3.682	3.881	3.813
	ASTSAN [110]	3.378	3.328	3.308	3.318	3.338	3.373	3.356
	URUST [144]	3.244	3.104	3.234	3.164	3.209	3.239	3.217
	SID [21]	3.602	3.318	3.423	3.323	3.498	3.473	3.504
	AesPA-Net [60]	3.861	3.448	3.622	3.493	3.537	3.552	3.696
	CAST [168]	3.741	3.433	3.562	3.488	3.512	3.562	3.626
	StyTR2 [23]	3.811	3.532	3.602	3.582	3.562	3.642	3.698
	EFDM [167]	3.692	3.353	3.567	3.443	3.522	3.493	3.584
	MAST [24]	3.478	3.119	3.174	3.219	3.164	3.343	3.341
	AdaAttN [95]	3.736	3.343	3.438	3.403	3.398	3.463	3.573
	AdaIN [63]	3.746	3.373	3.537	3.502	3.488	3.612	3.624
	DiffuseIT [80]	3.388	3.139	3.279	3.159	3.184	3.214	3.292
	InST [166]	3.493	3.229	3.323	3.279	3.289	3.428	3.401
	DiffStyle [67]	3.458	3.065	3.323	3.119	3.164	3.149	3.311
	CycleGAN [170]	3.674	3.378	3.376	3.453	3.398	3.425	3.540
	Gated-GAN [14]	3.881	3.532	3.597	3.542	3.542	3.776	3.739
StarGAN [18]	3.537	3.164	3.363	3.358	3.333	3.249	3.415	
StarGAN v2 [19]	3.493	3.204	3.333	3.224	3.289	3.388	3.390	
H-SRC [72]	3.224	2.945	3.085	3.025	3.070	3.055	3.130	
MSC [10]	3.562	3.249	3.483	3.284	3.378	3.423	3.463	
Photo-to-Cartoon	GANs N' Roses [20]	3.826	3.458	3.653	3.522	3.595	3.784	3.714
	U-GAT-IT [77]	3.690	3.378	3.530	3.439	3.479	3.464	3.574
	WBC [147]	3.578	3.362	3.453	3.374	3.408	3.311	3.480
	CartoonGAN [15]	3.577	3.179	3.507	3.338	3.224	3.373	3.451
	MSCartoonGAN [125]	3.552	3.299	3.393	3.343	3.328	3.358	3.448
Line Drawing	LGLD [13]	3.831	3.532	3.577	3.368	3.662	3.697	3.699
	APDrawingGAN++ [162]	3.682	3.353	3.612	3.348	3.468	3.597	3.579
	APDrawingGAN [161]	3.905	3.537	3.617	3.418	3.572	3.796	3.747
	Photo-sketching [85]	3.109	2.900	2.960	2.771	2.950	3.279	3.041
	DoodlerGAN [41]	3.308	3.144	3.134	2.905	3.119	3.279	3.212
Stroke-by-Stroke Painting	NP [109]	3.776	3.338	3.527	3.433	3.473	3.408	3.606
	MDRLP [64]	3.627	3.318	3.393	3.363	3.423	3.498	3.513
	SNP [171]	3.697	3.343	3.488	3.403	3.463	3.602	3.578
	Stroke-GAN Painter [145]	3.893	3.433	3.513	3.423	3.664	3.725	3.722
	PaintTransformer [94]	3.653	3.375	3.443	3.378	3.491	3.564	3.552
	Intelli-paint [127]	3.985	3.226	3.586	3.441	3.786	3.786	3.775
	Im2Oil [137]	3.901	3.315	3.688	3.412	3.878	3.823	3.762
	RST [79]	3.866	3.443	3.557	3.389	3.927	3.886	3.753
PST [98]	3.987	3.586	3.732	3.443	3.998	3.923	3.862	
Average	3.650	3.318	3.453	3.349	3.448	3.510	3.533	

Note: All painting results are classified into categories according to the generating procedure and art styles.

APDrawingGAN [161] gained higher scores than most. Paintings generated by DiffStyle [67], ASTSAN [110], DiffuseIT [80], and H-SRC [72] obtained scores lower than 3. This means these paintings have poor line expressions. The texture column compares the stroke texture of the test artworks. MAST [24] and H-SRC [72] obtain scores lower than 3; however, AesPA-Net [60], APDrawingGAN [161], StyTR2 [23], CAST [168], and PST [98] obtain scores higher than 3.6. That means these methods express stroke texture well. Methods obtaining high scores, especially PST [98] (3.823), present clear stroke textures in their paintings. In the color column, most of the methods score higher than 3 except photo-sketching [85], MAST [24], DiffStyle [67], H-SRC [72], and DoodlerGAN [41]. For the content comparison, only H-SRC [72], photo-sketching [85], and DoodlerGAN [41] obtain a score lower than 3. Scanning Figure 11, the images generated by photo-sketching [85] lose too much content. Thus, the line drawings or sketches, when compared with other paintings with rich contents, only gain lower scores. When compared in terms of art style

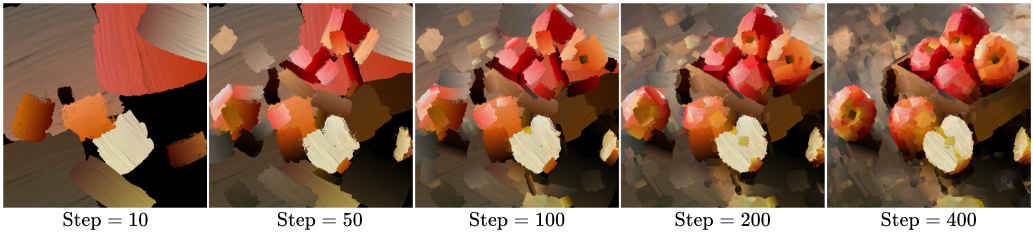


Fig. 14. Example of the painting process.

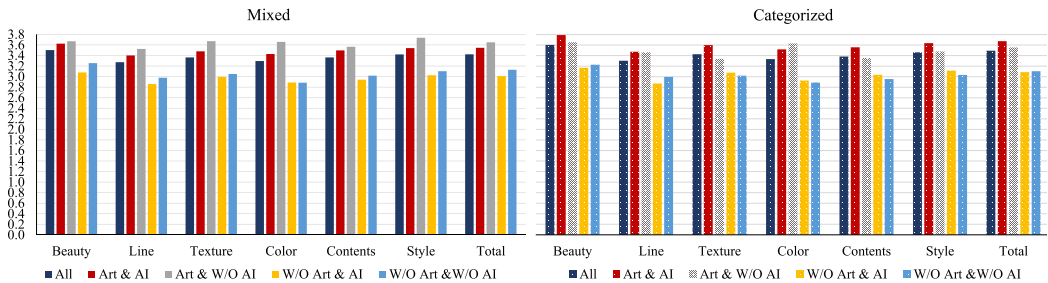


Fig. 15. The average scores of different background users in the mixed test and categorized test.

recognizability, only the paintings generated by H-SRC [72] obtained low scores (2.940). In other words, most of the participants cannot recognize the art style of the paintings created by H-SRC [72]. Table 5 shows the scores of the six-dimensional evaluation index on the classified artworks. The artworks are divided into four groups: style transfer/transform, photo-to-cartoon, line drawing, and stroke-by-stroke painting. Some of the artworks created stroke by stroke also exhibit the painting process images (Figure 14). In the user study Step 2, the scores were significantly higher than those of Step 1, especially since the number of scores below 3 was much fewer. The reason is that in the second test, users were informed of the style type and the image generation method so that users had a fuller understanding of the object they were evaluating. Therefore, users would be more tolerant and accepting of some less distinguishable options, thus giving higher scores. In the beauty column of Table 5, results of PST [98], AAMS [159], Im2Oil [137], APDrawingGAN [161], and Intelli-paint [127] obtained higher scores than most others. Especially, in the style column, the lowest score is higher than 3, which means that when users are informed of the styles and generation methods, their scores for artworks will be more accurate in the style confirmation item. In addition, it is in line with the principle of fairness to evaluate paintings by classifying them according to their styles and generation methods.

To conduct a more detailed analysis of the user study, we have sorted and classified the scores of the users based on their backgrounds. Figure 15 shows the scores of all artworks by five backgrounds of users: all users, users with artistic backgrounds who understand AI art, users with artistic backgrounds but do not understand AI art, users without artistic backgrounds but understand AI art, and users without artistic backgrounds who also do not understand AI art.

The analysis identified that the average scores of users with artistic backgrounds are higher than those of other users, whether in artworks-mixed or artworks-categorized tests. In the artworks-mixed test, users with an artistic background but no knowledge of AI art gave the highest scores, followed by users with an artistic background and knowledge of AI art. In the artworks-categorized tests, users with an artistic background and knowledge of AI art gave the highest scores except for the color item, followed by users with an artistic background but no knowledge of AI art. Especially

in the color item, the latter group gave the highest scores. Interestingly, in the two-step user study, the average scores given by users with an artistic background were higher than the average scores given by all users. Among users without an artistic background, in the artworks-mixed test, the scores given by users who understand AI art are lower than those who do not understand AI art in every category. In the categorized test, only the Beauty and Line items have lower scores from users who understand AI art compared to those who do not. Overall, in both tests, users who understand AI art gave lower scores than those who do not.

6 Challenges and Opportunities

AI technologies have been applied in many fields, including industry, art, and education, and have attracted significant attention. Methods for creating digital art are diverse, and the performance of these is steadily rising. However, there are still many challenges as well as opportunities. First, when converting a photo to an artwork, the balance of fidelity and creativity is still an ill-posed issue. Second, for painting/drawing methods, the creation order of generating an artwork is still a machine order and very different from the human order. Third, for most learning-based methods, the framework almost generates one art style instead of multiple styles. Fourth, it is difficult to generate artworks without reference images; in other words, existing methods have to refer to an input image to finish the painting process. Fifth, the existing evaluations for AI artworks (conducting user studies) are still subjective. However, there are still many opportunities for AI artworks in areas such as science and technology big-bang society [4]. There are requirements and opportunities for AI artworks in many fields, such as social community, education, art, and commerce.

6.1 Challenges

6.1.1 Fidelity vs. Creativity. Creativity has a profound impact on society [16, 163], especially in art. No matter whether we are considering style-transform AI artworks or art-style-reconstruction artworks, existing methods can ‘almost’ turn a photo into an artwork. Therefore, it is worth discussing the fidelity and creativity [50] of the results. Unfortunately, most painting/drawing methods have difficulty in achieving high fidelity because of the art style representation. For example, some methods (e.g., [7, 94, 123, 171]), although presenting the stroke texture of oil painting well, produce results that lose much detailed content owing to the invariant stroke shape or type. The method in the work of Huang et al. [64] also mimics the oil-painting process and can generate high-fidelity results when giving a large number of strokes, but the high-fidelity result is almost a photo rather than an oil painting because the strokes lack oil-painting stroke textures. In summary, turning a photo into a painting is a creative task requiring the result to not be the same as the photo itself, but the fidelity requiring the preservation of as many details as possible is still a difficult challenge, and we have yet to deliver pleasing results consistently.

6.1.2 Creation Order. Most painting/drawing methods claim that they can mimic the human painting/drawing process. In reality, they model stroke generation to render a large number of strokes onto the canvas to finish the creation of an artwork. However, the generation process is so different from the human painting process that they ignore the creation order that humans follow. In particular, when human artists create artwork, such as an oil painting, they tend to draft the main objects by lines first and then paint the background and the objects progressively. It is worthwhile to teach machines to really mimic the human painting process so as to reveal the mysterious veil of art creation, even though it is difficult to achieve this task. If we make a step to achieve the real human painting process, we make the machine painting more intelligent and closer to the human artist; if we endow the machine or computer with inspiration and motivation

for its creation (as pointed out by Hertzmann [56, 57]), then we may claim that the machine or computer can create art.

6.1.3 Abstract Art. Existing methods for creating AI artworks usually refer to the input image to re-create the artwork. However, a human artist can create artwork without real referent objects thanks to their human inspiration and imagination. Consequently, teaching a machine or computer to create artworks without reference images is a very challenging task. Although Xu et al. [155] achieved the generation of images from fine-grained text, the result was photorealistic and could not really be called artwork. Elgammal et al. [32] generated abstract artworks with their creative adversarial networks, but the model itself could not name the artwork according to its creation. In other words, this model just generates abstract images but does not know what the image is or what meaning the image represents. However, researchers can obtain inspiration from these two works, since the combination of text-to-image and abstract artworks can prompt areas of consideration and development for future AI art creation.

6.1.4 Multi-Style. Chen et al. [14] managed to generate multiple styles of results within an unified framework for image style transfer. It is popular to design a model to address multiple tasks; however, it is difficult to design a model that paints with multiple art styles. Although some works [64, 94, 171] could change the visual representation of the results by replacing different stroke styles, the art style stayed the same, almost close to oil paintings. Can machines or computers create different art styles of artworks within the unified framework? Similar to a human artist who can create a watercolor painting, a pastel painting, and an oil painting, seemingly by changing their painting tools, can a painting system create different art styles of paintings by changing its stroke style? It is an interesting and challenging issue for both artists and computer scientists.

6.1.5 Aesthetic Evaluation. Aesthetic evaluation is a critical issue for AI artworks. Some works [33, 45, 55, 61, 103, 108, 133] argued that aesthetic evaluation is important to develop methods for AI artworks. Especially for such diverse types of AI artworks as mentioned in the work of Rosin and Collomosse [115], a fair and scientific evaluation system is very important. In this article, we propose an evaluation system to cover several types of AI artworks so as to unify the diverse evaluating methods as well as make the evaluation fair when facing different types of AI artworks. However, even the proposed evaluation system is still based on user studies. Can we evaluate AI artwork and its methods via computing indexes? The proposed six-dimensional evaluation index may give some ideas and inspirations for the following research. For the development of AI artworks, fair, objective, and scientific evaluation is still an important and challenging area to be addressed.

6.2 Technological Advancement

To address the aforementioned challenges, the following technological advancements need to be achieved. First, the development of advanced image synthesis techniques and creative algorithms is necessary to enhance the fidelity of paintings and exhibit greater creativity. This can be accomplished by improving technological or algorithmic models such as CNNs, GANs, transformers, and DMs. Second, sequential modeling and reinforcement learning techniques should be utilized to enable AI to mimic the creative sequence of humans, from composition to detail refinement. For instance, by simulating the painting process of artists through deep learning techniques, a system can be developed that adjusts based on feedback during the creative process, allowing robots to more intelligently imitate the artistic creation sequence of humans. Third, exploring unreferenced generation techniques and inspiration and imagination modules is crucial to enable AI to create abstract artworks without specific input. This can be achieved by advancing unsupervised learning and

generative model-related technologies, while introducing a natural language processing based inspiration and imagination generation module. Additionally, through multi-task learning and style transfer modules, AI can process multiple artistic styles within a single framework and dynamically change brushstroke styles, resulting in works of various styles. Finally, the introduction of computational aesthetics evaluation metrics and the proposed six-dimensional evaluation system is essential for objective, fair, and scientific evaluation of AI artworks. This can be accomplished through IQA (Image Quality Assessment) algorithms and visual aesthetic feature extraction techniques.

All of these technological advancements rely on powerful computing capabilities and sufficient data support. Therefore, it is necessary to continuously enhance computing power and collect more diversified art datasets for model learning and training. By achieving these technological advancements, significant breakthroughs can be made in improving the quality, creativity, and diversity of AI artworks while promoting the further development of human-machine collaborative creation.

6.3 Opportunities

6.3.1 Social Media Requirements. The application of AI artworks in the social media community is very popular. In an era of ever-higher aesthetic aspirations and requirements, self-actualization and self-creation are areas of increasing attention and demand resources accordingly. Current techniques and algorithms cannot meet the demand of interaction and creation for everyone. Whether via social application software or on social websites, people are enthusiastic about making their own virtual characters or turning photos they have taken into artworks. However, it is difficult to make high technology and applications accessible universally for all people. First, the operation of creating an artwork based on a photo should be convenient and easy. Second, the method itself should have a small model size and a short inference time. Last but not least, the aesthetic quality should be acceptable to a relevant proportion of people.

6.3.2 Education Requirements. If the virtual artworks are visible but untouchable, that reduces subjective feelings: real artworks give a more direct sensory experience. When talking about direct sensory experience, painting artwork by oneself must be the act that gives the most comprehensive sensory experience. However, learning to paint from scratch is so difficult that most people do not know how to start. Not everyone who likes to paint needs or wants to go to school to learn how. Learning to paint by referring to videos or websites is popular; even so, it is not convenient for people who want to paint a certain artwork. Imagining that an application in your mobile phone can generate any artwork process according to your input, is this not more convenient or interesting? Such AI-aided art education can enrich individualized art education [156], which will bring more opportunities and possibilities for art education.

6.3.3 Art Diversity. AI technologies bring diversity and possibility for all kinds of art. GAN-based methods in particular have made a visual feast of style transfer or feature texture fusion. In traditional art history, it is always humans who create and present art. In this AI era, can computers really create art and diversify the presentation of art, differentiating from human art? As Hertzmann [57] gave a viewpoint, computers cannot make art because they have no creation, motivation, or emotion, but people do. In addressing the motivation and emotion of computers, we may have a long way to go, and it is not only the issue of AI artworks. Is it impossible for AI to create enriching forms of art and occupy a place in art history? The answer is no! We can, at least, make efforts to apply collaborative intelligence to the creation of digital art. As mentioned in the work of Wilson and Daugherty [149], humans should collaborate with AI so that, when creating a new artwork, we have a clear motivation and emotion, and even create an amazing artwork out of our imagination. Meanwhile, Cécile Paris pointed out that collaborative intelligence is the next

scientific frontier of digital transformation [153]. It must be an interesting task to achieve the collaboration of AI and human artists to create a new form of art, and collaborative intelligence must do something wonderful in this task [3].

6.3.4 Commercial Values. Since AI artworks can be used in many scenarios, it is necessary to discuss the value of AI artworks. Cetinic and She [12] proposed that the novelty of AI art should be taken into account when we talk about the values of this type of artwork in the context of art history. This type of art, as *generative art* [30], has been extensively theoretically and practically explored in the past few decades [29]. Recently, Chohan [17] noted that there is a category of blockchain-based virtual assets known as NFTs (non-fungible tokens, attracting an incredible amount of interest from investors in a very recent and short period. Digital artworks can be added to the growing list of uses for the blockchain technology that is now becoming a part of modern life in application such as accounting and auditing, agriculture, AI, business supply chains, and creative and artistic endeavors [138]. Hong and Curran [59] also investigated the price value of machine-made artworks compared with man-made artworks by user studies. The work found that man-made and machine-made artworks are not judged equivalent in their artistic value. The authors pointed out when the participants are told that the artworks are made by machines, then the evaluation is not influenced compared with participants not knowing. We can predict that AI artworks can be traded online and offline in the future, and people have a stable evaluation of artworks. Of course, we should take into account that the sale and subsequent reaction to the work resurrect venerable questions regarding autonomy, authorship, authenticity, and intention in computer-generated art [104].

6.3.5 AI Evaluation for AI Artworks. Inspired by some works [22, 70, 112], we focus on making a unified evaluation system for AI artworks. Note that the unified system contains several items (color, content, stroke texture, style, and beauty), and for a certain type of artwork, certain items should be chosen. For example, line drawings without color design should choose content, stroke texture, style, and beauty without the color item. We conduct a comparable experiment to find out the relation of the six items and different types of artworks. We first design the user study with all the artworks put together, composing the questionnaire. We then compose the second questionnaire by classifying the artworks according to art types. In these two questionnaires, the evaluation items are the same. From the analysis of Section 5, we determine that the six evaluation items are reasonable, and for different types of artworks, certain items gain very low scores, demonstrating that they are inappropriate for that type. We propose a unified evaluation system for AI artworks, where the items are flexible and are to be chosen for a certain type of artwork. This six-dimensional evaluation index is able to cover many types of AI artworks as well as assign the abstract aesthetic evaluation into several concrete dimensions. However, it is still not enough to cover all kinds of AI artworks, and it needs to be developed into a more objective evaluation system based on computational aesthetics in the future.

7 Conclusion

We investigated current learning-based methods for AI artworks and classified the methods according to art styles. In particular, we first classified the methods into style-transform methods and art-style-reconstruction methods according to the artwork generation process. For the style-transform field, we further classified the methods as NST, GAN based, and DM based. For art-style-reconstruction methods, we classified the methods according to the traditional artistic art style of the generated results, such as line drawing, oil painting, ink wash painting, pastel painting, and the more specialized robot paintings. Furthermore, we proposed a consistent evaluation (based on previous works) for AI artworks and conducted a user study to evaluate the proposed AI artwork

evaluation system. This evaluation system contains six items: beauty, color, texture, content detail, line, and style. The user study demonstrates that this evaluation system is suitable for different styles of artwork. This consistent evaluation system containing six items is sufficiently flexible to enable the selection of certain items when evaluating different styles of artwork. There are many more art styles than those considered in this article, and it is our hope that, in the future, further art styles will be generated and more methods can be evaluated by a unified evaluation system.

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