

Review

Virtual reality painting: A structured review of a decade of innovation

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Abstract: Various studies have widely utilized virtual reality (VR) in painting creation. However, there has been few conclusive studies on VR painting. The present systematic literature review describes the current state of knowledge and practices using VR in painting and provides guidance for painters and scholars focusing on human computer interaction design by critically appraising and summarizing the existing research. It also outlines a wide range of results yielded by quantitative, qualitative and mixed-method studies to investigate potential benefits, difficulties, and effectiveness of VR painting. Overall, 44 studies published from 2013 until 2023 were analysed, with 16 articles introduced the hardware technology and interaction mode of VR painting, 17 articles introduced the beautification method of VR painting, and 11 articles focused on the application of VR painting in different fields. Implications for practice and research are discussed in detail, as the hardware selection, interaction, and physical simulation in VR painting scenes.

Keywords: virtual reality; painting; sketch; human-computer interaction; systematic review

1. Introduction

Since the advent of the new age hailed as the year of the metaverse in 2021, artists have become increasingly active in exploring and experimenting with new forms. Among these, virtual reality (VR) technology has provided an innovative blueprint for traditional art forms, including painting. As a profound computer simulation technology, VR empowers users to immerse themselves deeply in artificially created virtual worlds, offering endless possibilities for artistic expression in the era of technology [1]. Virtual reality painting is a novel three-dimensional creation mode born from the fusion of virtual reality simulation technology and the art of painting. When creating artwork, artists need to wear a virtual reality headset, adjusting the angle of the virtual space through head movement and rotation, and complementing this with hardware devices like interactive controllers to complete creations within a virtual three-dimensional scene [2]. Coupled with interactive design, this allows audiences to interact with the artwork. Commercial VR painting software often provides a variety of virtual scenes, such as starry skies, seasons, and different weather conditions, along with a rich selection of painting tools, such as watercolor pens, brushes, and graffiti tools. It also includes auxiliary features like line references and beautification to inspire creators with limitless creative inspiration, creating new and unique art pieces. This brings viewers a visual experience distinctly different from traditional painting.

It is noteworthy that after its explosion in popularity in 2016, VR has once again attracted the attention of major tech companies both domestically and internationally in 2021, driven by the metaverse frenzy. Gradually, it has been utilized as a fundamental technological approach for creating virtual environments

and scenarios within the concept of the metaverse [3,4]. As a remarkable application of VR technology, VR painting provides an immersive and highly unrestricted creative experience. It is regarded as a unique artistic method within the metaverse and has gradually emerged as a significant research interest among academic communities both domestically and internationally in recent years. Hence, a comprehensive review and summary of the VR painting domain will assist us in better adapting to and leading the “metaverse era” driven by meta design.

2. Review methodology

This research adopts a systematic literature review approach, which primarily includes the following steps: identifying the problem, setting criteria, searching for literature, filtering literature, statistical analysis, and writing the review. Focusing on the topic of the development and current state of research in VR painting, keywords such as “virtual reality painting”, “virtual reality drawing”, “3D painting”, and “mid-air painting” are used for a combined search in the ACM core database. The search spans the past ten years (2013–2023), yielding a total of 461 pieces of literature related to the topic.

Based on the research objectives, this paper further refines the selected literature through the following steps: (1) the content of the literature is related to painting or sketching; (2) the type of publication is empirical research, excluding reviews and theoretical articles; (3) considering the similarities and reference value between drawing in AR, MR environments and VR, the decision to retain a paper is based on its content; (4) references cited in the relevant literature are used as supplemental data sources. Following these filtering criteria, the literature data were cleansed and organized, ultimately referencing 44 pieces of relevant literature (Figure 1).

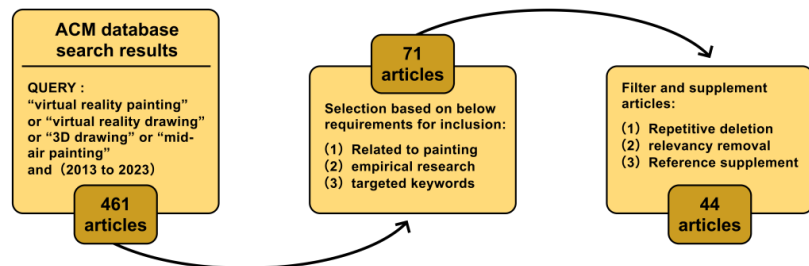


Figure 1. Flowchart for screening articles.

3. The development history of VR painting

The advancement of virtual reality technology has endowed us with the capability to create 3D brushstrokes. VR painting, which originated in the 1990s, is a new form of artistic creation. The SANDDE system, developed by the Canadian film and digital technology company IMAX, was the first to apply VR painting in the field of animated film production [5]. In 2001, Keefe et al. [6] developed a system named CavePainting, which operates within an immersive virtual reality environment, providing artists a natural interface to craft 3D scenes. The CavePainting system is akin to drawing on a large canvas, allowing users to freely

create, observe their work from various perspectives, and interact with the computer through simple gestures and tools.

Since 2014, the emergence of several commercial VR painting software has offered new insights into traditional painting methods. Tilt Brush [7], developed by the San Francisco interactive design studio Skillman & Hackett (later acquired by Google in 2015), is a VR painting application widely used in various industries including industrial design, sculpture, painting, and animation creation. Users can mimic painting gestures using hand controllers to achieve a range of brushes, colors, and painting effects, thus creating 3D images. In addition to Tilt Brush, Oculus has released several VR creation software, such as Oculus Quill, which is specifically designed for drawing storyboards, shot scripts, and artwork [8]. This application introduces animation creation and editing functions, allowing creators to produce digital painting-based animated works, offering a new dimension to artistic expression. Oculus Medium offers more than just painting capabilities, creators can also sculpt and model in an immersive environment. Gravitiesketch [9] is commonly used for car model design, allowing for elegant and reliable sketching and modeling operations. The newly launched Gesture VR [10] aims to provide the same experience as live drawing classes, with its most notable feature being its support for up to four players to connect and sketch together in the same space (**Table 1**). Overall, virtual reality offers a more liberating experience for creation. It not only challenges the traditional creative thinking of artists but also inspires their creativity, achieving many artistic effects that traditional painting cannot reach.

Table 1. Development and features of virtual reality painting software.

Number	Year	Name	Features
1	1990s	SANDDE	Wearing specialized glasses, paintings are recognized through an electronic pen and sensors
2	2001	Cavepainting	Provides flat support, allowing the artwork to be viewed from different angles
3	2014	Tilt Brush	Fully functional, with a wide range of applications
4	2015	Oculus Medium	Capable of 3D modeling
5	2016	Oculus Quill	Equipped with animation capabilities, a professional artistic creation tool
6	2017	Gravity Sketch	Applied in product or industrial design, supports 3D sculpting and VR modeling
7	2022	Gesture VR	Multiplayer online painting

With the arrival of the 5G era, rapid advancements in computer technology, and changes in human life and work driven by the internet and mobile devices, technological innovation has emerged as a new driver for virtual reality development, propelling VR into a new phase. Following the 2021 metaverse frenzy, research in virtual reality technology, its underlying support, has expanded across multiple domains, including various art and design fields, further advancing VR painting.

Recent research has increasingly focused on developing painting modes that better meet human needs and offer a richer sensory experience. Türkmen et al. [11]

studied the impacts of continuous guidance, discrete guidance, and no guidance on painting speed and accuracy, while also exploring the underlying human factors. They focused particularly on differences in eye gaze behavior and eye-hand coordination. This study broadened the research perspective on VR painting, designing painting assistance tools starting from the human aspect, thereby providing users with a more intelligent and more accessible VR painting mode. ThermalPen [12] is designed to enhance user experience by ingeniously integrating visual cues from pen stroke colors and textures with temperature stimuli generated by the pen body, creating a unique visual-tactile feedback mechanism. This means that as users select different colors and textures for drawing, the temperature of the pen adjusts accordingly, overcoming the sensory feedback limitations of traditional drawing tools and significantly enriching the sensory experience during the creative process.

It's noteworthy that Bodylab has emerged as the first virtual reality tool designed for the painting and shaping of full-body avatars [13]. It employs highly realistic human models as canvases, offering functions such as drawing, sculpting, and applying particle effect animations. Bodylab has been utilized in various dance performances, notably in a large video projection where dancer Alina Lucifer, through her virtual avatar in Bodylab, presented "Betwixt & Between," a work directed by Vinzenz Schechner. In the 30-minute performance, the virtual avatar transformed through 31 pre-created forms, vividly conveying themes of transition, identity, and change explored in the work. The capability to create full-body avatars in Bodylab reveals its immense potential, not only proving the feasibility of quickly constructing full-body avatars with VR technology but also demonstrating significant value in fields like metaverse socializing, artistic creation, and gaming.

4. Human-computer interaction in VR painting

4.1. Hardware devices and interaction methods

Creating art in a virtual reality environment starts with the selection of hardware media. VR hardware mainly includes display devices, hand interaction devices, and dedicated chips, among others. Hand interaction devices in virtual environments provide participants with a more immersive sensation, such as touch and force feedback [14,15]. VR hand interaction devices are rapidly evolving, giving rise to various interaction modalities, including but not limited to interactions based on tablets and styluses, handheld controllers, and multisensory interactions. The hardware devices and interaction methods (**Table 2**) explored below are primarily related to hand interaction devices, namely the concept of a "paintbrush" in drawing creation.

Table 2. Articles on hardware devices and interaction methods.

Category	Authors	Keywords	Methodology
Stylus interaction	Pham DM and Stuerzlinger W (2019) [16]	3D pointing, input devices, virtual and augmented reality	Experiment and questionnaire
	Elsayed H et al. (2020) [17]	Virtual reality; 3D user interfaces; sketching; pneumatic actuation; vibrotactile actuation; haptics	Experiment, questionnaire and short questions
	Arora R et al. (2017) [18]	Virtual reality; 3D drawing; motor ability; visual factors.	Experiment

Table 2. (Continued).

Category	Authors	Keywords	Methodology
Stylus interaction	Drey T et al. (2020) [22]	sketching; pen and tablet; mid-air painting; virtual reality; interaction metaphors; design space;	Experiment, questionnaire and semi-structured interviews
	Gasques D et al. (2019) [23]	Augmented reality, sketching, prototyping, PintAR	N.A.
	Gasques D et al. (2019) [24]	Augmented reality, sketching, prototyping, HoloLens	Experiment and own experience
	Arora R et al. (2018) [25]	3D drawing, design sketching, augmented reality	Experiment and questionnaire
Handheld controller interaction	Shi R et al. (2023) [27]	Virtual reality, object selection, pointing selection, dense environment, bare-hand interaction, head-mounted displays	Experiment, questionnaire and semi-structured interviews
	Jiang Y et al. (2021) [28]	VR, 3D sketching, hand-based interaction	Experiment, questionnaire and semi-structured interviews
	Kim Y et al. (2018) [29]	Hand motion; scaffolding; 3D sketching; product design	Experiment, depth interviews and questionnaire
	Bohari U et al. (2018) [30]	Mid-air interactions; 3D sketching; random forest; intent recognition; curve modeling	Experiment and questionnaire
Sensory interaction	Zhang X et al. (2021) [31]	Virtual reality; immersion; comfort; balance design	Experiment, Multinomial questionnaires and systematic evaluation
	Li Z et al. (2023) [33]	Human-centered computing, human computer interaction, interaction paradigms, VR	Experiment
	Ranasinghe N et al. (2018) [34]	Multisensory VR; virtual reality; multimodal interaction	Pilot test, experiment and questionnaire
	Reiter K et al. (2022) [35]	Multimodal interaction, virtual reality, VR, gaze interaction, handheld menus, on-body menus, extended reality, XR	Pilot test and questionnaire
	Wolf E et al. (2019) [36]	Speech and gesture, creativity, design, 3D user interfaces	Experiment and questionnaire

4.1.1. Stylus interaction

In three-dimensional design, the pen is a very powerful design tool. Pham et al. [16] conducted a user study on several input devices (including a mouse, controller, and a 3D pen-like device) in virtual reality and augmented reality systems. The results indicated that the pen is more powerful than the controller, enabling users to manipulate the cursor more swiftly, reduce errors, and achieve higher throughput. Participants also showed a preference for using the pen as an input device. Elsayed et al. [17] designed a sketching pen for virtual environments—the VRSketchPen, aimed at enhancing the accuracy of sketching. This pen incorporates two types of unconstrained tactile aids: pneumatic force feedback and vibratory haptic feedback, to help users improve drawing precision and reduce motion and depth errors. Arora et al. [18] compared the performance of electronic pen drawing in virtual reality environments with and without a physical support surface. The results showed that when a physical drawing surface was available, the average overall deviation of the target strokes significantly decreased. Therefore, in some studies on VR painting, tablets are used as auxiliary tools to interact with the electronic pen for co-creation [19–21]. Drey et al. [22] designed an application named VRSketchIn, utilizing a 6dof tracking pen and tablet as input devices. Drawing inspiration from the design concepts of Gasques’ team [23,24] and Arora’s team [25] in using pens for drawing

within AR systems, they combined unconstrained 3D mid-air drawing with more precise 2D plane-based drawing. Experiments indicate that participants highly rated this mode. Both 2D and 3D sketches could be used for different tasks, fully leveraging the strengths of each input device.

4.1.2. Handheld controller interaction

In VR or 3D drawing, a 6-DOF input device is often used, allowing the device to follow the user's hand movements to create strokes. This method makes the operation more flexible and faster, and is commonly referred to as freehand drawing [26]. The handheld controller interaction mentioned here includes not only using interactive handles and gloves for input but also encompasses input through gestures. The most pressing issue in VR painting is how to accurately capture user movements. Shi et al. [27] proposed a grid-based freehand pointing technique (with the aid of an interactive glove). Through comparative experiments, they demonstrated the superiority of this controller over other pointing techniques, allowing users to select targets more conveniently and quickly, which aids in the accuracy of drawing. Jiang et al. [28] proposed the first VR sketching system with a hand-based physical proxy called Handpainter, which allows users to easily sketch on the palm of their hand. The system uses the non-dominant hand as a canvas proxy and the index finger of the dominant hand as a 3D pen. Through a series of intuitive gesture operations, it enables users to effortlessly use various features, offering higher usability compared to existing VR painting systems. However, gesture operations in the Handpainter system mainly rely on capturing through interactive gloves. Exploring the possibility of palm drawing without gloves is a direction for further development in the future. Kim et al. [29] developed a novel drawing mode that integrates gesture movement and pen drawing as two input methods. Its innovation lies in the entire process of hands-free interaction without wearing any devices, mainly relying on head-mounted displays to capture hand movements. Initially, simple hand gestures are used to sketch the rough outline of an object, which is then refined in detail using an electronic pen once a basic shape is formed. This approach can help designers quickly and roughly present their ideas in the early stages, sparking new inspiration. In the later stages, the assistance of an electronic pen facilitates more detailed depiction of the object. In current commercial VR painting software, gestures or controllers are usually required to indicate the intent to start and stop drawing. Bohari et al. [30] proposed a new method that determines whether to continue drawing based on the user's finger trajectory and the geometric features of the drawn shapes, without the need for additional actions. This greatly reduces the extra physical exertion during the drawing process.

4.1.3. Sensory interaction

Immersion and comfort are two important indicators for evaluating the quality of virtual reality content. In VR painting, immersion can make one concentrate on the virtual painting creation process, feel pleased, and thoroughly enjoy the process of creating artwork; good comfort levels can reduce the sensation of dizziness caused by the virtual reality environment. Building on practical experience in VR interaction design, the team led by Zhang et al. [31] has explored design principles for balancing immersion and comfort in virtual reality environments. These principles emphasize

the importance of incorporating natural interaction and multi-channel stimulation compensation. However, existing VR painting systems often focus solely on visual sensations, neglecting other channels, which to some extent diminishes the advantages that virtual reality environments bring to artistic creation. Previous studies have shown that multi-sensory interaction can activate the brain and promote participation of various sensory parts of the body [32]. Based on this, the team led by Li et al. [33], through participatory design, invited 12 participants to jointly explore issues related to immersion in VR painting programs, and proposed design ideas for integrating a variety of sensory interactions, including visual, auditory, tactile, and olfactory, into VR painting. At the same time, the Season Traller system [34] can customize scents and tactile feedback based on natural scenes, where different natural objects trigger different forms of feedback; for example, grasslands emit the fragrance of grass, and trees can produce the effect of wind blowing through leaves, combining multisensory interaction modes to bring users a more immersive experience. Look & Turn, proposed by Reiter et al. [35], is a VR painting menu interaction method that combines gestures and gaze. It uses gaze to implicitly access menu groups and items, and arm rotation and pinching gestures for navigating menus and modifying parameters. This design not only simplifies the operation process but also offers the advantages of one-handed operation and easy expression. Similarly researching menu interaction modes, Wolf et al. [36] designed a Multi-Modal Toolbox (MTB) based on voice and gestures, proving it to be superior to a Uni-Modal Toolbox (UTB) in terms of usability, fatigue, and presence. Therefore, introducing multi-sensory interaction modes and engaging users' senses beyond just vision undoubtedly brings new ideas to artistic creation in virtual reality environments.

Overall, electronic pens and tablets, due to their similarity to traditional painting mediums, are more easily accepted by users and usually offer better drawing effects. The combination of two-dimensional plane drawing and three-dimensional air drawing provides both a sense of experience and accuracy. However, how to smoothly switch between these two modes remains an issue that requires further research. Meanwhile, device-free hand interaction and multi-sensory interaction modes simplify the operation process, aligning more closely with users' expression habits and following the trend towards natural behavior interaction. The integration of multiple senses helps to greatly enhance the sense of immersion, bringing users a more enjoyable experience. Yet, the accuracy and latency of this mode are central factors in improving user experience. Therefore, where the balance lies between current technological maturity and the choice of hardware and interaction modes, remains a topic worthy of deep contemplation in the field of VR painting.

4.2. Painting modes and guiding techniques

Current VR systems have afforded artists and designers a more streamlined approach to crafting 3D imagery. However, existing research indicates that the process of air drawing within a virtual reality setting demands additional exertion for movement and multi-angle coordination, resulting in images that lack the detail and precision found in those produced by alternative methods [37]. Against this

backdrop, numerous teams have engaged in research on guidance and enhancement techniques within VR painting software, encompassing visual guidance, painting beautification, integration of plane and space, and haptic feedback (**Table 3**), aimed at facilitating the creation of more intricate, accurate, and aesthetically pleasing drawings and sketches within the virtual reality.

Table 3. Article on painting modes and guiding techniques.

Category	Authors	Keywords	Methodology
Visual guidance	Kang J et al. (2021) [39]	3D structured sketches, virtual reality, visual guidance	Pilot test
	Machuca MDB et al. (2019) [40]	Virtual reality drawing, 3D user interfaces, drawing	Experiment and questionnaire
	Machuca MDB et al. (2017) [41]	Virtual reality drawing; 3D user interfaces; depth perception; spatial cognition	Experiment and questionnaire
	Arora R et al. (2018) [25]	3D drawing, design sketching, augmented reality	Experiment and questionnaire
	Türkmen R et al, (2022) [11]	3D sketching, eye-gaze, user study, VR, guides	Experiment and questionnaire
	Kusunoki M et al. (2023) [43]	Virtual reality, multiple viewpoints, 3D modeling	Experiment , questionnaire and user feedback
Painting beautification	Fişer J et al. (2015) [44]	/	N.A.
	Kwan KC and Fu H (2019) [45]	3D sketching; augmented reality; mid-air drawing; mobile interaction; relative drawing; 3D concept design	Experiment and user feedback
	Barrera Machuca MD et al. (2017) [46]	Virtual reality drawing; sketching; 3D user interfaces	Experiment and questionnaire
	Son J (2021) [47]	/	Experiment
Integration of plane and space	Drey T et al. (2020) [22]	Sketching; pen and tablet; mid-air painting; virtual reality; interaction metaphors; design space	Experiment, questionnaire and semi-structured interviews
	Arora R et al. (2018) [25]	3D drawing, design sketching, augmented reality	Experiment and questionnaire
	Machuca MDB et al. (2017) [41]	Virtual reality drawing; 3D user interfaces; depth perception; spatial cognition	Experiment and questionnaire
Tactile feedback	An SG et al. (2017) [19]	Automotive design; experience prototyping; design methodology; 3D sketching; haptic feedback; virtual reality	Experiment, questionnaire and focus groups interview
	Elsaye H et al. (2020) [17]	Virtual reality; 3D user interfaces; sketching; pneumatic actuation; vibrotactile actuation; haptics	Experiment, questionnaire and short questions
	Hofmann PP et al. (2023) [12]	Virtual reality, 3D sketching, creativity, user experience, haptics, pen-input, thermal	Pilot test
	Otsuki M et al. (2017) [48]	Painting system, mixed reality, augmented reality, input device paintbrush visual, haptic feedback	Experiment and questionnaire

4.2.1. Visual guidance

Broadly speaking, the inaccuracies of three-dimensional images can be categorized into two main types: lack of shape similarity and stroke precision [18,38]. Unconstrained visual guidance aids users in creating their intended figures by providing assistance during the drawing process but does not perform optimizations or similar operations, making it a drawing approach worth further investigation. Fluid3DGuides [39] is an unconstrained drawing guidance technique that enhances the precision of sketching. This system supports the continuous recognition of the user's drawing intentions and automatically infers and draws baseline lines based on the existing stroke information and its location, providing

users with continuous visual guide lines that immediately disappear once the user has finished drawing, thus avoiding visual interference with subsequent drawing processes. Mayra proposed a drawing guide technology similar to Fluid3D-Guides, but the difference lies in that the Smart3DGuides system does not rely on using existing stroke information, but serves merely as an unconstrained visual guide for three-dimensional sketching. Based on the current user's view direction, controller posture, and existing strokes, Smart3DGuides provides users with depth cues and directional indications to help avoid errors during drawing [40–42]. Similar to the design of Smart3DGuides, Arora et al. [25] conducted a comparison between sketching on traditional physical surfaces and sketching in virtual reality environments, identifying the lack of a physical drawing surface as the main reason for inaccuracies in virtual reality drawings. Based on this, they introduced a set of indicative interactive guides called SymbiosisSketch, aimed at guiding the design of future VR-based drawing tools. Building on previous research, Türkmen et al. [42] recently proposed a hybrid, segmented visual guidance design—discrete visual guidance—which provides visual assistance for accuracy while also leaving room for creative freedom for the user. Furthermore, considering that creators need to constantly move their bodies to observe different sides of the target object during the drawing process, which adds an extra burden, the team led by Kusunoki et al. [43] designed a system within the interface that offers multiple viewpoints. This system allows users to switch perspectives with the press of a button, providing a more guided and less labor-intensive drawing mode.

4.2.2. Painting beautification

Painting beautification is a common feature in VR painting software. One of the biggest challenges during the beautification process is the ambiguity of user input. The intentions behind users' creations often differ significantly from their actual brushstrokes. Moreover, as the number of basic shapes in a piece increases, this problem becomes more complex. Fišer et al. [44] proposed a beautification system for hand-drawn sketches that can automatically correct output images. Although this system is mainly aimed at the creation of two-dimensional works, its line optimization algorithm was later used in a 3D painting beautification system by Kwan et al. [45]. They designed a type of line beautification tool that can connect the endpoints of lines to the adhesion points of other lines to ensure the precision of the artwork, allowing users better control and adjustment of lines. The multiplanes system [46] also provides a stroke beautification feature, introducing the concept of a beautification trigger point. When a user starts drawing a stroke, the system recognizes it as a straight line, an arc, or a circle based on the geometric relationship between the positions of the controllers. If the geometric relationship doesn't resemble any known shape, the system retains the stroke as a general curve that follows the motion of the hand. Unlike other systems, when using Multiplanes, users don't need to perform any gestures or actions for beautification; it automatically triggers the beautification effect when reaching the beautification trigger point, allowing users to focus more on the creative process. The emotion brush, emoPaint [47], incorporates a variety of line textures, shapes, and colors, allowing users to freely control the emotional expression in their painting, such as associating anger

with thick, dark lines and sadness with slow, downward-moving lines.

4.2.3. Integration of plane and space

Tobias Drey and others conducted a usability test of the VRSketchIn system with 6 participants and concluded that 2D surface drawing is suitable for creating lines or planar objects, while 3D air drawing is appropriate for shaping volumes [22]. Thus, combining two-dimensional and three-dimensional techniques can complement each other's advantages and have a positive impact on creative painting in VR. In recent years, researchers have proposed some methods that combine planar and aerial techniques, providing new ideas for the development of drawing in virtual environments. Arora et al. [25] designed a mixed sketching system that combines 2D and 3D approaches to design detailed 3D objects. Its key feature is the transformation of unorganized 3D curve collections into surfaces. These surfaces can serve as canvases for 2D sketching, allowing for more accurate drawing and control over the shape of curves and surfaces, offering higher flexibility and control for VR painting systems. The approaches proposed by the team of Machuca MDB [41] and team of Kim [19,29] are somewhat similar, primarily involving the use of gesture motions to quickly generate rough and approximate 3D shapes as frameworks, then using a pen on a tablet to add finer details to the 3D sketches.

4.2.4. Tactile feedback

Tactile feedback refers to the simulation of tactile sensations found in the real world, allowing users to feel realistic touch in a virtual reality environment. Generally, haptic feedback includes a variety of sensations, such as temperature, vibration, or resistance simulation. In VR painting, haptic feedback plays an important role by providing feedback that helps users achieve a more realistic and immersive experience in a virtual environment. The VRSketchPen [17] combines pneumatic force feedback and vibration haptic feedback to help reduce motion and depth errors while drawing. The ThermalPen [12], a novel 3D sketching pen, associates the texture and color of strokes with different thermal properties. For example, a fire texture would cause an increase in temperature, while an ice texture would lower the temperature in the pen, providing realistic tactile feedback to enhance the creator's ability. The MAI Painting Brush [48] is a special type of brush that simulates the feel and feedback of a real paintbrush. Users can achieve a sensation similar to painting on real objects when using this brush. Although this brush is primarily designed for painting in mixed reality, the haptic feedback mechanisms proposed in the article are still suitable for application in virtual reality environments.

Overall, current research has approached the issue of insufficient accuracy in VR painting from multiple angles. The focus has primarily been on software performance enhancements, including adding reference and assistance features within the software to help users draw more accurately. This also involves using technologies such as machine learning to analyze and understand user intentions, automatically optimizing and correcting drawing outcomes. Additionally, improvements have been made in user input devices and interaction methods to increase drawing precision. However, it's important to note that addressing the issue of insufficient precision in VR painting is a complex and long-term task. In line with

the trend of technological development, while optimizing VR devices and software, it is essential to deeply explore the human brain and the perceptive features of human eye gazing behavior [49–51] towards artworks. This approach aims to make targeted improvements in the precision of VR painting. Further research needs to comprehensively consider factors such as technology, human perception, and user experience, to create more accurate and aesthetically pleasing paintings.

4.3. VR painting application scenarios

Although VR painting is currently a niche form of art, with the advancement of underlying virtual reality technology and the arrival of the metaverse era, it is gradually becoming a form well known and embraced by art creators and the general public. It is also increasingly being applied in different fields such as mural restoration and stage design, while spawning various application scenarios including animation creation and mental health therapy.

With the advent of virtual reality painting software such as Quill and Tilt Brush, artists have discovered new pathways to explore and experience VR painting, gradually merging virtual reality technology with the art of painting in a unique fashion. French artist Anna Zhilyaeva was invited to perform a live VR painting at the Louvre in France, creating “Liberty Leading the People” [52]. After completion, it was possible to walk directly into the artwork, observing the surrounding environment from a first-person perspective and interacting with the painting content through controllers.

In the field of cultural heritage preservation, VR painting has become an important tool for professional preservationists and archaeologists involved in heritage restoration work [53,54]. The team led by Ovidia Soto-Martin digitally restored 18th-century murals at the St. Augustine Church [55], allowing people to appreciate millennial mural art across time and space. The RestoreVR [56] interactive system proposed by Xinyi Fu’s team enables users to experience the restoration of Dunhuang murals in a virtual reality setting, positively impacting public interest and awareness towards mural conservation.

Moreover, VR painting can also add endless charm to stage performances. At the 2022 CCTV Lantern Festival Gala, VR painting was combined with the “Tiger Dance,” integrating traditional lion dance, mechanical tigers, and VR technology, embodying the enduring charm of Chinese excellent traditional culture. On the stage of the Beijing Winter Olympics, VR artist Shi Shanshan incorporated VR painting with elements of Chinese style, offering a new rendition of the Winter Olympics theme song “Together for a Shared Future” in a national style version, showcasing the beauty of Eastern culture to the world [57].

VR painting is often used to create animated works, showcasing unique features distinct from traditional animations and overcoming the limitations experienced when viewing 2D works. An early representative work is “Dear Angelica” created by illustrator Wesley Allsbrook [58], featuring vivid colors and delicate brushwork. Utilizing the compositional methods of virtual reality space, it presents an astonishing visual effect and won the Best Virtual Reality Animation Experience Award at the 2015 Sundance Film Festival. Cutler et al. [59] used Oculus’s VR

animation tool “Quill” to re-arrange themes of environmental protection and women’s empowerment in works like “Baba Yaga” and “Tree.” Scholar Qin Liu created a VR animation of the ancient city within “Along the River During the Qingming Festival,” offering viewers a new first-person “peep” perspective [60]. The viewing angle expands from focusing on parts of the scene to encompassing a panoramic view, giving audiences the sensation of “walking into the scroll.” Additionally, the characteristics of VR headsets empower viewers with the autonomy to change viewing angles based on personal interest within the same scene, thereby enhancing their engagement.

VR painting is also frequently utilized in the medical and psychological therapy fields, transforming rehabilitation training into a special experience in virtual reality, effectively alleviating patients’ fear and apprehension towards the treatment process. In terms of physical rehabilitation, Baron et al. [61] have elucidated the potential of virtual reality in therapeutic interventions, proposing VR art game therapy in a study focused on upper limb physical therapy. This method, through painting activities, promotes bodily stretching, thereby improving the physical condition of participants. Although VR painting mainly focuses on upper limb activities, it also offers valuable references for physical therapy (PT) rehabilitation training for patients with lower limb mobility restrictions. Additionally, VR is beginning to be used as a supplementary tool in psychotherapy for treating conditions such as post-traumatic stress disorder, depression, anxiety, and other psychological illnesses [62–65], with VR painting, thanks to its highly immersive creative environment, expanding ways of creative expression and opening rich therapeutic avenues for art-based psychotherapy. Several pilot studies using Tilt Brush [66–68] have proven the effectiveness of VR painting in processing psychological emotions, capable of inducing positive emotions and reducing stress.

5. Challenges and development prospects

Under the impact of the “metaverse” market, the iterative upgrading of virtual reality technology is facing infinite opportunities and challenges, also bringing new possibilities to the art of painting. Currently, as we step into a new era of digital art, VR painting, as a means of creating virtual digital art, has initially formed a development direction that synchronizes hardware devices with interactive methods, positively propelling the development of future artistic creation. However, whether from the perspective of hardware comfort or the accuracy of painting, there is still a certain gap from the envisioned goals. Through systematic discussion, this section summarizes the opportunities and challenges of VR painting and proposes potential research needs to elucidate the future prospects.

5.1. Hardware development enhances the VR art experience

In recent years, VR painting has emerged as an innovative means of artistic expression, providing artists with a new way to present their creativity in three-dimensional form to the audience. With the widespread availability of commercial VR devices, it has become easier for the general public to experience VR art, but two major challenges still persist.

Firstly, current VR artwork is primarily exhibited through online platforms and panoramic videos, which leads to the representation of works on traditional flat media, losing their special spatial effects. This issue reflects the real challenge facing the development of virtual reality technology, that is, the high cost of hardware, which makes it difficult to achieve popularization. As a result, more accessible modes of display are adopted, but at the expense of the immersive experience.

Secondly, the comfort of VR devices is poor. Most current VR controllers are mainly operated by “wrist rotation,” which performs poorly for painting that requires precise input of stroke positions. There is an urgent need for new holding methods to enhance painting accuracy. The tripod grip at the rear end, discovered by Li et al. [69] and others, can reduce target selection time and increase accuracy, bringing a better experience to VR painting.

Additionally, the hands-free interaction mode, which follows human natural behavior, is a trend for future development and should be the focus of researchers. Some studies in chapter four have already proven its superiority and feasibility in the field of painting. However, research should prioritize solving the accuracy and lag time of hands-free control in order to offer users a more perfect experience while conforming to the trend. Therefore, to truly unlock the artistic potential of VR painting and create immersive artworks, future development should focus on hardware advancements while continually optimizing the functionality and performance of the devices.

5.2. New ways to optimize VR painting creation

Compared to traditional art forms, VR painting has not yet truly established its unique advantages and is more seen as a novel method of creation. It requires artists to master the manipulation of the three-dimensional world, as well as possess artistic skills. However, the works created in practice often fail to achieve a clear and refined effect, and the creation process may not always be smooth, even possibly inducing dizziness and fatigue. Despite modern VR painting systems introducing a variety of auxiliary tools, such as visual guidance, line optimization, multi-plane referencing, and haptic feedback, which to some extent lower the entry barrier to VR painting, creators still face multiple challenges in considering the width, depth, height, and spatial positioning and angles of objects, undoubtedly adding complexity to the creation process.

In our previous analysis of painting modes, we discovered that leveraging the special perception of our brains towards artwork or the unique structure of the human eye that produces gaze behavior could enhance the precision of drawing by starting from human perceptual abilities. Beyond this, richer multi-sensory feedback is a necessary direction for future research: it’s worth considering the combination of the precision of two-dimensional plane drawing with the freedom of three-dimensional painting, and integrating sensors and triggers into electronic pens or controllers to simulate more realistic touch and pressure. Meanwhile, by integrating 3D audio technology, the addition of spatial environmental sounds and sound effects to VR painting scenes can immerse creators in realistic studios or natural environments. It’s also possible to adjust the direction and distance of sounds in real-

time based on the audience's location and orientation, offering a more realistic and immersive auditory experience. These solutions undoubtedly have the potential to significantly enhance the efficiency and quality of the VR painting experience.

Furthermore, by introducing complex task decomposition mechanisms [70] into the painting process, the learning efficiency of beginners can be significantly enhanced. This method not only helps to substantially improve the painting skills of creators in the short term but also enhances the educational aspect of VR painting and the sense of achievement for the operator. It is a cost-effective yet highly effective instructional strategy, although currently, there is relatively little research in this area.

5.3. Collaborative creation mode to alleviate loneliness

The current state of virtual reality is often seen as a somewhat isolated experience, unlike traditional painting which allows multiple people to collaborate on a piece of paper, creators of VR painting typically need to wear specialized VR equipment to enter a virtual world for independent creation, lacking interaction and a sense of companionship. Although existing research, such as the Multi-A-Painter system [71] through WebVR technology and URL access for collaborative painting attempts, and the Gesture VR sketching application by Nick Ladd and his team that enables multiple users to connect and create sketches together in the same virtual space, have provided solutions to some extent. However, when a large number of users access simultaneously, there are still pressing issues such as server load problems, network latency, and security challenges that need to be addressed.

The "metaverse" represents the fusion of virtual and real worlds, further diminishing the differences between the two. To realize the future development of the metaverse, in-depth collaboration among multiple users is required. The collaborative creation mode will become a key support for the development of the metaverse. Artworks created in VR that support collaborative creation can become artworks within the metaverse or one of the essential elements for constructing virtual spaces. Based on the concept of co-design, the content of the metaverse can be enriched further. Therefore, developing a high-performance, secure, and reliable collaborative VR creation platform is a research direction that needs to be focused on at present.

5.4. Copyright protection and management of digital works

As VR creation technology continues to develop and become increasingly popular, the issue of copyright protection it faces is expected to become more prominent. Firstly, due to the digital nature of VR painting, works are easily copied, distributed, and altered, which may infringe upon the copyright of creators. Secondly, the virtual characteristic of VR painting increases the difficulty in regulation and copyright protection, potentially leading to copyright infringement and abuse. Blockchain technology, with its decentralized, traceable, and tamper-proof characteristics, has shown natural advantages in copyright protection [72].

By leveraging blockchain technology, creators can register the copyright of their VR works, making this copyright information available for query by any user,

providing a reliable reference for potential buyers and relevant institutions. At the same time, in terms of copyright transactions, blockchain technology can help establish a dedicated VR painting copyright exchange platform, not only offering a professional venue for copyright transactions but also displaying and promoting works, paving a broader market and audience for artists. In general, by actively integrating blockchain technology, it has shown great potential in protecting and promoting copyright of VR paintings, and also provided an effective solution for more secure and reliable transactions.

6. Conclusion

In this constantly evolving era of the metaverse, VR painting, as a cutting-edge form of artistic creation, presents infinite opportunities and challenges. This new creative method, which combines the advanced technology of virtual reality with traditional painting, is still in the early stages of development. It faces numerous challenges such as the comfort of the devices, the fineness of the artwork, and copyright protection, making it challenging to fully replace traditional painting as an independent art form. However, its unique advantages and broad development prospects are undeniable. Technological progress will bring revolutionary changes to the field of art creation. Moving in this direction, we look forward to more interdisciplinary cooperation and the emergence of innovative ideas, allowing VR painting not only to merge with dance, music, and traditional culture among other art forms but also to push VR painting and digital art into a new era full of vitality and depth.

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