

# InfinitePaint: Painting in Virtual Reality with Passive Haptics Using Wet Brushes and a Physical Proxy Canvas

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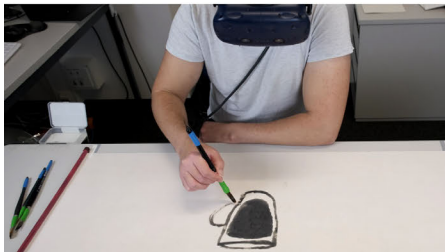
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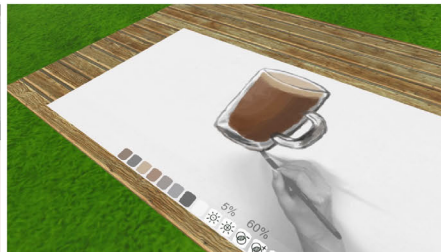
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a) Painting on real paper in VR



b) VR user viewpoint



c) Resulting digital painting



**Figure 1:** We present InfinitePaint. a) A Virtual Reality user paints with a real wet brush on special paper that temporarily turns black upon contact with water and turns blank again when dry. b) Our system digitizes newly added strokes and renders them persistently with the chosen color and opacity in the virtual environment. c) Users can create complete digital paintings with the haptic experience of brushes on paper without using up art materials and with digital capabilities enabled.

## ABSTRACT

Digital painting interfaces require an input fidelity that preserves the artistic expression of the user. Drawing tablets allow for precise and low-latency sensing of pen motions and other parameters like pressure to convert them to fully digitized strokes. A drawback is that those interfaces are rigid. While soft brushes can be simulated in software, the haptic sensation of the rigid pen input device is different compared to using a soft wet brush on paper. We present InfinitePaint, a system that supports digital painting in Virtual Reality on real paper with a real wet brush. We use special paper that turns black wherever it comes into contact with water and turns blank again upon drying. A single camera captures those temporary strokes and digitizes them while applying properties like color or other digital effects. We tested our system with artists and compared the subjective experience with a drawing tablet.

\*Both authors contributed equally to this research.

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## CCS CONCEPTS

• **Human-centered computing** → *Virtual reality*.

## KEYWORDS

Digital painting, virtual reality, mixed reality, passive haptics, traditional art, brush input

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## 1 INTRODUCTION

With the ubiquity of digital devices in the modern world ever-increasing, the number of people who own a touchscreen device is greater than ever. Now, anyone with a tablet has the ability to create art quite literally with the touch of their fingers. Despite this, digital painting has struggled to attract many professional artists practicing *traditional* art media. Indeed, simulating various forms of art such as watercolor or acrylic is challenging [18], but in the last decade the quality of these simulations have improved enormously [12], also due to competition in the realm of commercial applications (e.g., *Adobe Photoshop* [1] or *Procreate* [34]). However,

what is generally missing for the traditional artists is a tactile experience that is comparable to painting with a brush on paper or a canvas—a gap unable to be bridged by drawing on a glass screen with a stylus. While there do exist a few solutions for mimicking the experience of a *pencil* for both writing and drawing on paper in research and on the market (such as the *ReMarkable* tablet [56]), little research has been done to retain the haptic sensations of painting real strokes on paper using a wet brush. Instead, many previous interfaces simulate brush strokes [8, 20, 22, 49] and the interactions of the watercolors with the paper [6, 16, 52]. Those approaches are input-agnostic and as such are not concerned with the tactile sensations of painting provided by the input device—rather, they can be orthogonal to the used input. Vision and graphics methods allow for stylizing complete input images and making them appear as watercolor and ink paintings [9, 11, 41, 73]. However, this is different from simulating the painting process on a per-stroke level, as the latter allows for artistic expression with every brush stroke.

Many digital tools use simple, potentially noisy, stroke input and apply beautification [26, 46] or warp more complex shapes around those simple strokes [36]. Such stroke beautification and assisting systems are beneficial for novices [7, 40]. However, artistic expression can potentially get lost, if the system or user relies on it too much. Researchers were also attracted by the potential of Virtual Reality (VR) for sketching and painting in 3D [3, 19]. The six degrees of freedom per hand enable three-dimensional sketches. However, we believe that much potential resides in combining VR with the rich haptics and experiences of traditional painting.

We present InfinitePaint, a Virtual Reality painting system that uses specialized paper as a proxy for creating digital paintings using wet brushes. Figure 1 provides an overview of our approach and prototype. We use special paper that turns black wherever it comes into contact with water (Figure 1 a). Instead of tracking the brush head and simulating the strokes, a camera captures the real brush strokes including subtle interactions between the paper and the water. Users are immersed in VR and see newly painted strokes (Figure 1 b), which we digitize according to the current state of a virtual color picker (i.e., the chosen color and opacity, see Figure 1 b bottom). The physical strokes dry over time, allowing users to infinitely paint on the same canvas and to fully create digital paintings from scratch (Figure 1 c). Taken together, we contribute:

- The InfinitePaint approach of using a real water-based brush and specialized paper with disappearing strokes to paint in VR. We bring the capabilities of digital painting interfaces to the traditional method of painting including its tactile sensations.
- An InfinitePaint prototype implementation that showcases the potential of our approach. Besides the core concept, we implemented a few example capabilities that demonstrate the combination of both physical and digital painting techniques.
- A user evaluation to test our approach and prototype as well as to compare it to traditional and digital methods in terms of input capabilities and subjective experience. We describe quantitative as well as qualitative results, and provide a set of example paintings created by participants.

In this paper, we describe our concept, provide implementation details and report the results of our evaluation. We conclude with advanced techniques and use cases.

## 2 RELATED WORK

Our work is related to previous efforts in digital painting with real brushes as well as previous research about drawing and sketching in VR. In our work, we are primarily concerned with the *input* for painting digitally (as opposed to, e.g., simulating brushes [21]).

### 2.1 Pen and stylus input

Pen devices for on-surface input which have the affordances of analog pens and the ability to digitize strokes comprise a powerful general purpose input method that dates back to the early days of HCI [66]. Digital pen devices are commonly used on capacitive screens or other active sensing surfaces—both commercially [71] and in research [48]. Active haptic feedback aims to circumvent the limitations of the low-friction surface of digitizers, e.g., by simulating the haptic sensations of paper through vibrations [14]. Other approaches aimed to move away from specialized surfaces towards passive surfaces [47, 57], into mid-air [33, 63] (also with force-feedback [32]), or the combination of on-surface and mid-air [72]. Most relevant to our work are interfaces that utilize the *passive* haptic properties of physical paper [37]. Paper-based digital pen input can also be augmented either with specialized electronic paper (e.g., *IllumiPaper* [38]), by using projection mapping (e.g., *PenLight* [64]), or by using Mixed Reality (e.g., *HoloDoc* [43]). Previous research also used pen input for artistic use cases [36]. For instance, *IR2s* by Xie et al. [73] turns individual digital strokes of a sketch into Sumi-e brush strokes.

Even though pen input is also used for tasks different from painting (e.g., annotating, sketching), this body of previous research shares very similar goals to our work. Analogously to digital pens aiming to pertain the affordances and tactile sensations of writing with a real pen on real paper, we aim to achieve the feeling of using a real wet brush on a canvas.

### 2.2 Sketching and painting in mid-air

With the rise of virtual and augmented reality, researchers started utilizing new input and output methods for sketching in three-dimensional space [19]. Ongoing research over the years investigated not only sketching and note-taking for productivity [43], but also different techniques to increase the potential of artistic painting and sketching in mid-air [2, 3]. Within the last few years, there have also been commercial systems emerging that utilize VR for sketching in 3D, e.g., *Tilt Brush* [29] and *Gravity Sketch* [30]. A common drawback of sketching in mid-air is the lack of haptic feedback and physical support. Therefore, researchers investigated the use of active haptic feedback to circumvent this limitation. The *DAB* system [5] uses a Phantom haptic input device and simulates the brush strokes. Otsuki et al. [54] developed a system that enables painting on virtual objects in mid-air in a Mixed Reality environment with an active haptic feedback device. Even though our approach also uses VR, we are less concerned with mid-air input and 3D sketches, and more with using VR as an enabling technology for creating digital 2D paintings using the inherent passive haptic properties of soft brushes and a canvas. With this, the brush can remain at a small form-factor without the need for actuators, and the precise tracking and simulation of the brush head is circumvented by directly capturing the actual painted strokes.

## 2.3 Physical painting tools as inputs

Many previous interfaces utilize real physical brushes as input for digitizing the painting process. Instead of active haptic devices, the use of traditional tools and materials preserves the tactile sensations as well as audio and visual impressions that are crucial in the artistic process [51]. Several approaches to digital real-time painting systems involving real brushes (as opposed to styli) have been published in the literature [21], ranging from brushes with infrared fibres as with *IntuPaint* by Vandoren et al. [70], capturing the footprint of a real brush using a camera [74], and systems involving painting with wet brushes on smooth surfaces as in *FluidPaint* [69]. Claesen et al. [17] use an infrared camera system that is installed below the table to capture brush footprints at a high precision. The *MAI paint brush* by Otsuki et al. [53] enables painting on real objects with a real (dry) paint brush. *FlexStroke* by Liu et al. [45] is a brush device with a flexible tip that mimics the use of soft brushes.

The aforementioned systems were generally perceived very positively in user evaluations. However, a main drawback is that they rely on custom specialized hardware. To address this, researchers also presented work that use commodity hardware. Yeom and Lee [74] use a real brush, which is captured by a webcam. While their motivation is similar to ours, their interface only captures the movements of a dry brush interacting with paper. All interactions of watercolor with the virtual canvas are simulated. In particular, the brush is approximated as an ellipse, leading to less expressive output compared to the actual interactions of paper, water and color. Chu and Tai [15] track the 6 DoF of a Chinese calligraphy brush and fully simulate the soft brush head. Li et al. [42] use a Kinect and a dry brush to convert Chinese characters into pre-defined images of objects and replace the character with those shapes.

The discussed works are very flexible approaches. However, systems that support wet brushes use a smooth surface like glass [69] and systems that support the use of real paper use a dry brush [74]. Thus, they do not support the passive haptic sensations of moving a *wet* brush on paper or a canvas. Furthermore, advanced techniques like smearing strokes can only be simulated.

## 2.4 Images and physical mediums as inputs

Research interest for using digital input specifically for painting grew over time [31]. This input can be whole images, e.g., to transfer the style of a real drawing or painting to a 3D rendering (e.g., *StyLit* by Fišer et al. [27]) or between high-resolution images [68]. The aforementioned *IR2s* system [73], which can convert individual strokes, can also make complete photos look like Sumi-e paintings.

Besides taking complete images as input, researchers also employed methods for extracting individual strokes on a canvas [44] to create enhanced digital replica. Similar to our approach, *iNkDraw* by Sekiya and Chihara [59] does not capture the tool, but rather the strokes. Specifically, they capture a dry erase marker on a clear plastic sheet, creating a digital replica of every stroke composing the picture. *MOD* by Momeni and McNamara [50] captures drawings in real-time, e.g., to project them on large surfaces for live performances. Both, *iNkDraw* and *MOD* are not compatible with using wet brushes on paper. Tan et al. [67] decompose a drawing into layers based on time lapse recordings so as to not only replicate the drawing or painting, but to also enable digital capabilities

afforded by the generated layers. Joolee et al. [35] track the brush position while the artist is painting with a real brush that applies actual ink to a real canvas using a sophisticated hardware setup and machine learning.

Those works have in common that the ink on the canvas is permanent, i.e., the goal of such systems is to exactly replicate the painting seen on the real canvas and hence it does not allow to paint infinitely with different digital capabilities.

## 2.5 Related work: Summary

In summary, there is a trade-off in previous research between high flexibility (e.g., simulating ink or using a dry brush without applying ink) and systems that preserve the full experience of applying ink to a canvas (aiming to create an enhanced replica of the physical painting). With our approach, we aim to combine the advantages of both sides of the spectrum, i.e., having the high flexibility of digital tools (e.g., functions like undo) while enabling the tactile properties of painting on paper with a real wet brush.

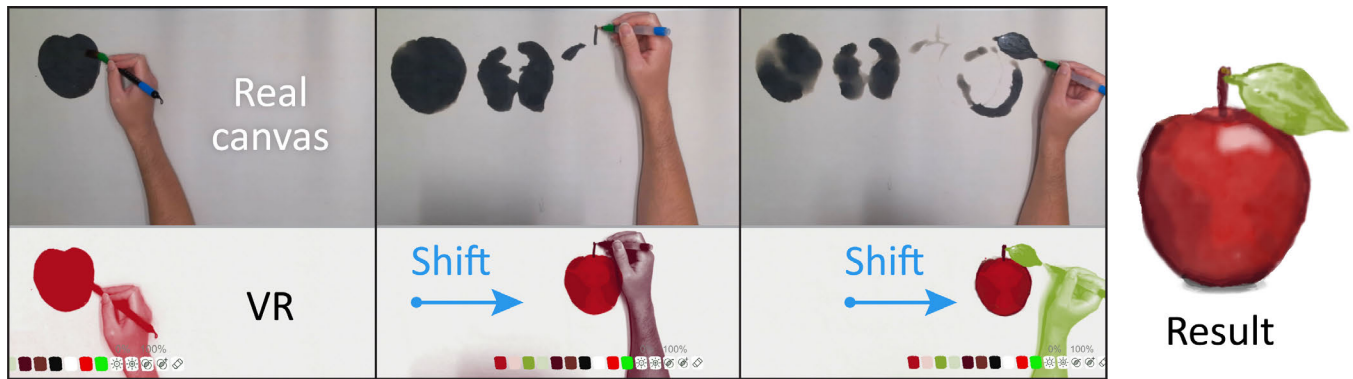
## 3 CONCEPT AND PROTOTYPE

We designed InfinitePaint to deliver the tactile experience of painting on canvas with wet brushes in VR while maintaining the convenience of painting continuously on the same canvas ad infinitum—without consuming ink or materials. The strokes are painted with wet brushes on specialized paper that turns black wherever it is wet and blank again as the paper dries. We capture the brush strokes painted by the user, all the while making them persistent in the VR environment. InfinitePaint renders each stroke with the color that the user chose from a virtual color picker.

Figure 2 shows an overview of the InfinitePaint approach (also see Video Figure A in the supplemental material). The system renders the brush and any currently painted strokes in VR in real-time, making it independent of any tracking or simulation. Moreover, any type of desired physical brush can be employed since the strokes are captured directly from the canvas. In particular, the captured stroke already contains feathering edges (especially for strokes that contain little water), which are essential for realistic looking brush strokes [49]. Therefore, in its most basic form there is no need to compute the flow of water or paint. In addition, we implemented an *eraser* tool (also present in the color picker). When this tool is active, then instead of adding colored virtual strokes, the user basically paints a mask on top of previously drawn strokes so as to erase parts of the painting.

### 3.1 Shifting

The wet regions of the paper need to dry (around 3 minutes, also depending on how much water is applied) before new strokes can be painted over them. There is therefore no way of detecting when a user paints over the same area twice in quick succession, since the paper will still be black where the original stroke was. This is of particular significance for painting, since layering over the same area is a prominent feature of the medium. In order to solve this problem, we use a *shifting* approach, whereby the strokes are moved virtually to a new, clear region of the physical canvas, so that our system can detect the new stroke drawn on top of the virtual one. VR users only see the previously captured strokes (made persistent



**Figure 2: The InfinitePaint concept.** The immersed user does not see the black strokes on the real paper (top). Users shift the virtual painting into free space on the canvas whenever they want to apply color on top of existing strokes. The paper dries over time, i.e., regions that have not been painted on for a while can be used again.

in the virtual painting) as well as the strokes that they paint in the moment. Users can shift around the virtual canvas (and the color picker with it) using a gamepad or VR controller held in their non-dominant hand. The painting area can be moved either to a new quadrant with a fixed grid layout or it can be continuously moved to a custom position. Figure 2 showcases the shifting principle. First, the user paints the main solid shape of an apple. By shifting the virtual painting to the right, the user can paint over the solid shape to add shading as well as the stalk and the leaf. In the meanwhile, the left part of the paper dries so as to be reused to add more shades, and the process repeats.

### 3.2 Prototype: Processing

We implemented our prototype of the InfinitePaint concept using Unity and the *Velt* framework [25]. Figure 3 shows the physical setup with the hardware and equipment (bold labels) that we utilize in our prototype as well as the software components. We will use this figure as a reference in the remainder of this section.

**3.2.1 Hardware and equipment.** We use a low-cost (~\$20) commercial paper scroll (‘magic paper’) whose original purpose is to practice Chinese calligraphy. The magic paper turns black upon application of water, and fades upon drying. Depending on the frequency of use, the magic paper can be reused for a long time before it needs to be replaced (we used the same paper for prototype development, for our user evaluation and for creating the examples in this work before the paper showed signs of damage). To render the brush and users’ hands in real-time as well as to capture strokes, we use the RGB output from an Azure Kinect (without depth).

Our prototype is intended to be primarily used with VR. We use an HTC Vive to render the virtual canvas horizontally on a virtual table that is aligned with a real desk. Alternatively, the system is also compatible with ordinary screens. In the screen version, we render the virtual workspace (including the users’ hands and brush strokes) from a top-view. This indirection is very similar to interacting with a drawing tablet without an integrated screen.

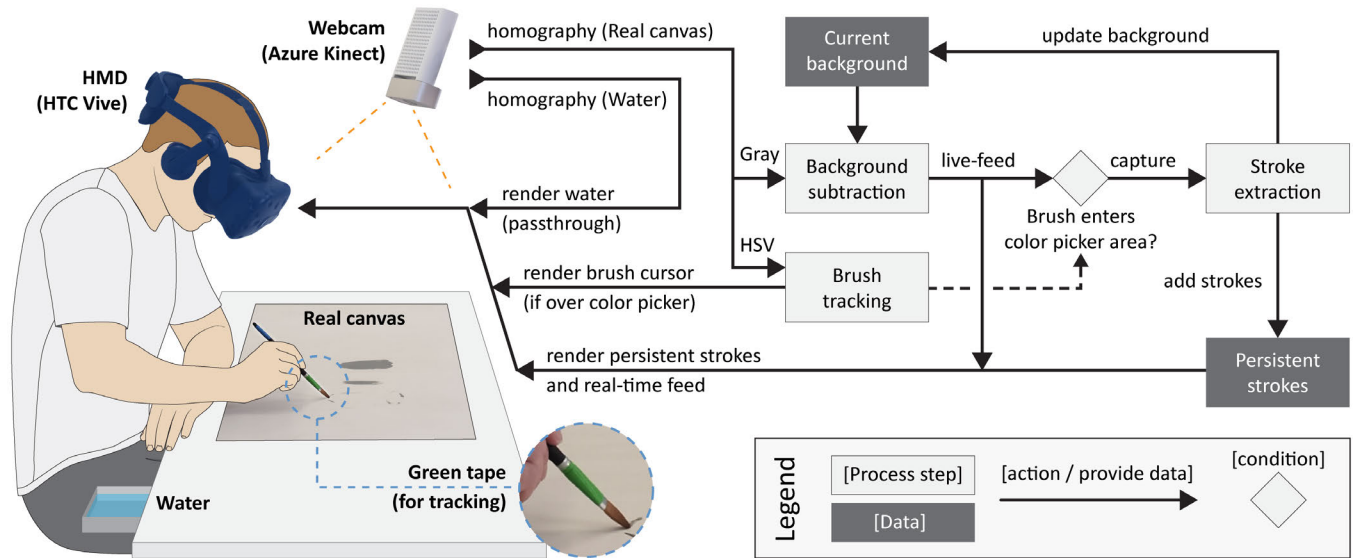
**3.2.2 Camera stream.** The webcam feed is the main input of our pipeline as it captures the canvas as well as the water reservoir.

Since the canvas lies flat on a table, we can use a homography (based on direct linear transformation [24]) to perspectively unwarp its contents. We pre-calibrate the canvas homography manually (i.e., the location of the corners in the camera feed), because the positions of the real canvas and the camera remain static. During runtime, we continuously take pixel samples from the edge of the canvas to normalize the feed to adapt to slightly changing lighting conditions, therefore normalizing the luminosity of the input. As shown in Figure 3, we convert the homography into two color spaces. For the ‘Background subtraction’ and subsequent steps, we convert the image to gray-scale, since the strokes on the canvas are black. For the ‘Brush tracking’, we convert the homography into the Hue-Value-Saturation (HSV) color space as it is based on chroma keying.

**3.2.3 Background subtraction.** By initially capturing the empty canvas (in addition to any static lighting artifacts such as shadows cast by the equipment), we can subtract away a background image from the live feed, resulting in an image where only the changes from the background are present. This processed real-time feed with previous strokes subtracted serves as one of the inputs for rendering and for the stroke extraction (Figure 3 middle to right).

**3.2.4 Brush tracking.** The brush tracking serves two purposes (also see ‘Brush tracking’ box in Figure 3). First, we detect whether the brush is below the currently active virtual canvas so as to trigger the ‘Stroke extraction’. Second, it turns the brush head into a cursor for selecting a color from the color picker whenever hovering over it. To facilitate tracking, we affixed green tape to the bottom of each brush. We use a simple HSV-based chroma key approach to locate the blob of this tape in the camera feed.

**3.2.5 Stroke extraction.** Whenever the ‘Brush tracking’ detects that the brush enters the color picker region at the bottom, we capture the canvas by saving the current image from the background-subtracted real-time video feed. The newly captured canvas replaces the old background image used in the real-time feed, in order that the recently painted strokes are also subtracted from any subsequent real-time images. The capture is then sent to the stroke extraction pipeline to make them persistent. It is only during this stage that stroke segmentation occurs.



**Figure 3: System configuration of our InfinitePaint prototype.** The raw RGB stream from the Kinect camera is processed with a homography and background subtraction, and displayed to the user, rendered above any persistent strokes. Additionally, if a ‘capture’ event is triggered (by moving the brush to the color picker) the stroke extraction pipeline is executed, after which we add the new strokes to the list of persistent strokes and update the stored background. The same webcam input is also used to render the water reservoir real-time passthrough so the user can see the reservoir and pick up water at all times.

To detect the contours in the image, we first apply a Gaussian blur to the ‘capture’ image, to minimize any noise. In practice, we use a sigma of 1, which still allows us to detect any small details (e.g. tiny droplets, dry-brush). Then, we apply a binary threshold to the captured image to detect the locations where the contours are present. We have manually set the threshold value so that the stroke is segmented without including any shadows or lighting artifacts that may still be present. This results in a *stroke map*, where white regions represent the canvas and black regions represent the strokes. In a later step, we use this as a mask to subtract any unwanted regions from the image. We also use the *stroke map* to find the super-bounds of the contours so we can crop the texture so that it only contains the necessary part of the captured image.

As an additional post-processing step, new strokes bleed into previously painted strokes. More information about bleeding including an example can be found in the supplemental material.

### 3.3 Prototype: Rendering

**3.3.1 Rendering live-feed of canvas.** The subtracted input is displayed constantly as a real-time video feed, spanning across the virtual canvas in the VR environment. The real-time video allows the users’ hands as well as the brush to be seen within the virtual canvas area, as shown in Figure 1 b. Strokes painted by the user at any moment are also visible in the real-time projection and are displayed in the selected color, so that the current stroke looks the same as the eventual rendered stroke. As we wish to display the whole content (strokes, hands, brush etc.) of the real-time video stream to the user, we do not need to do any stroke-hand segmentation. Only whenever the user goes to the color picker, (i.e., when the hand does not occlude the canvas), a ‘capture’ event occurs.

**3.3.2 Stroke rendering.** The ‘Persistent strokes’ that the ‘Stroke extraction’ generates (Figure 3 right) is primarily comprised of a set of alpha textures (single-channel). The darkness of the stroke on the image corresponds to the amount of water present on the canvas, and thus the intensity with which the stroke should be rendered. Therefore, we invert the ‘capture’ image, and subtract the *stroke map* to remove any noise in the background that is not part of the stroke. We normalize the stroke by the same value as in the real-time output. We use the image luminosity for the opacity of the stroke, ensuring that naturally lighter, less wet areas of the stroke are slightly transparent, compared to darker, wetter parts. This also allows the natural artifacts from the watercolor to be visible. Strokes are rendered by projecting the image texture onto a rectangle. Any additional per-stroke properties set by the users (e.g., color, opacity and brightness) are applied here. We explain additional tools such as the eraser or blur effect in subsection 5.1.

**3.3.3 Water reservoir video passthrough.** The immersed user needs to be able to pick up water during the painting process. Some of the brushes have a small reservoir of water in them, allowing the user to paint continuously on the canvas for long periods of time. However, most brushes do not have this feature. Therefore, to allow any brush to be used, we must allow the user to pick up water, which we facilitate by means of a passthrough (also see ‘Water’ in Figure 3 and the corresponding homography). A small video feed is situated to the right of the virtual canvas, displaying the real water to the user within the virtual environment. We manually aligned the passthrough with the location of the reservoir in reality. Alternatively, we selectively render the HTC Vive’s passthrough, enabling a fully aligned viewpoint between user and passthrough.

## 4 EVALUATION

To test the feasibility of our approach, we invited several amateur and professional artists to try out our prototype. We gathered quantitative and qualitative results in the form of subjective ratings as well as semi-structured interviews to compare InfinitePaint with traditional as well as digital painting.

### 4.1 Study design

Our study consisted of two independent blocks—one for comparing mediums and one for free-painting with InfinitePaint. Overall, the structure is similar to previous work [74] consisting of *Tutorial* painting with a given object to paint and *Free* painting. However, in our study, we compared three different painting mediums in the tutorial painting part, namely traditional painting, digital painting and painting with InfinitePaint. This corresponds to the three **conditions**: TRADITIONAL, TABLET, INFINITEPAINT. The user study was approved by the ethics committee of ETH Zürich.

### 4.2 Participants

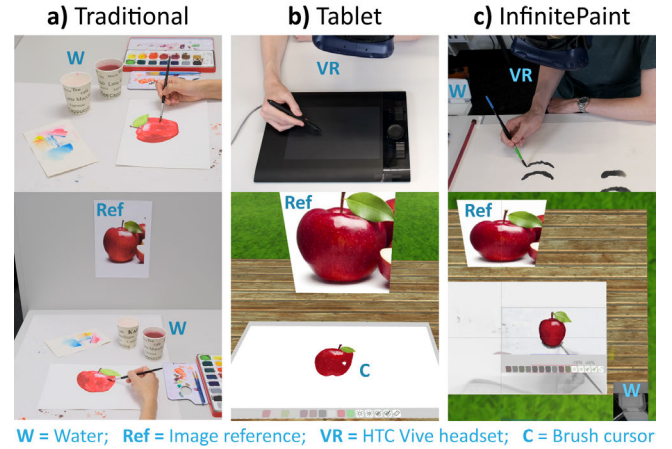
**4.2.1 Recruitment.** Our main requirement for potential participants was that they had basic knowledge in traditional painting, or more specifically, the usage of brushes. That is, persons with at least basic experience in any type of painting that involves brushes (watercolor, acrylic, oil etc.) were eligible to participate. We insisted on this criterion so as to not only collect quantitative data for measuring the user experience, but also to gain insights about artistic processes and how a system like ours can be utilized from an artistic perspective. We distributed flyers and reached out via mailing lists of institutions with professional artists to recruit participants.

**4.2.2 Demographics and previous experience.** 15 participants signed up for our study. One participant was removed during the course of the study due to inconsistent responses<sup>1</sup>, resulting in a final sample size of  $N = 14$  participants. 12 of the resulting participants were female, 2 were male. The participants were between 20 and 48 years old ( $M = 30.86$ ,  $SD = 8.29$ ). All of them had painted in traditional art media at least a few times before. 10 of them said they engage in “occasional small art projects”, and 1 of them described themselves as a hobbyist. 3 participants use digital art tools (drawing tablets) at a professional capacity. 7 participants indicated that they use VR either sometimes or often, whereas the remaining half of participants indicated that they use VR rarely or once to twice.

### 4.3 Apparatus

Figure 4 shows the apparatuses of all conditions and blocks. In the TRADITIONAL baseline, we used commercial watercolors (*Caran d’Ache*) and provided two cups of water as well as cold-press watercolor paper (Figure 4 a). We provided a print-out of an apple as a reference photograph (Figure 4 a bottom). For both digital conditions, we used an HTC Vive headset (Figure 4 b and c). We rendered the reference vertically inside the virtual environment (Figure 4 b and c bottom). For the TABLET condition, we chose a Wacom Intuous 4 (Figure 4 b). The apparatus for the INFINITEPAINT condition and for the second block is the same as described in section 3.

<sup>1</sup>The participant likely did not fully understand the questions, which led to inconsistencies between the qualitative and quantitative feedback.



**Figure 4: Apparatus of our evaluation for all three interfaces or mediums.** a) Standard watercolors and two cups of water (W) with the printed reference photograph. b) Painting with a Wacom tablet in VR. c) Our InfinitePaint prototype in VR including a camera pass-through for picking up water (W). In Block 2, we only used InfinitePaint.

### 4.4 Tasks and procedure

Each session started with the participant being greeted by the experimenter followed by a brief explanation of the study’s purpose. The participant then filled out the consent form as well as the pre-questionnaire and could ask questions at any time. The pre-questionnaire contained questions about demographics and previous experience with painting (traditional and digital), as well as previous exposure to VR. Afterwards, the two-block study began.

**4.4.1 Block 1.** The first block, which was also the main part of our study, consisted of three conditions to collect primarily quantitative data. Each condition was a painting medium, namely, traditional painting (we chose watercolor), painting with a drawing tablet, and painting with InfinitePaint. We refer to the latter two conditions as **digital conditions** hereafter. Drawing tablets are generally mostly used with conventional screens or built-in displays. However, researchers also started to investigate the benefits of drawing tablets in VR for 3D tasks [23] or 2D tasks [10, 28] suggesting that those can be feasible for input in future VR systems. To maximize comparability in terms of input, we ultimately chose to use a VR headset for both digital conditions, because the VR output might otherwise create unintended advantages or disadvantages between those conditions. In each condition or medium, participants had to paint an apple. They had a photo of an apple as a reference photograph (printed in the TRADITIONAL condition or displayed in front of them in VR in the digital conditions). We counterbalanced the digital conditions (TABLET and INFINITEPAINT), whereas all participants started with the baseline TRADITIONAL, since we are primarily interested in comparing the digital conditions. For both digital conditions, we used the same VR environment and provided a reduced tool set. This allowed the participants to focus on the input and passive haptics, instead of the set of features and the visual appearance of the resulting painting. Concretely, in both

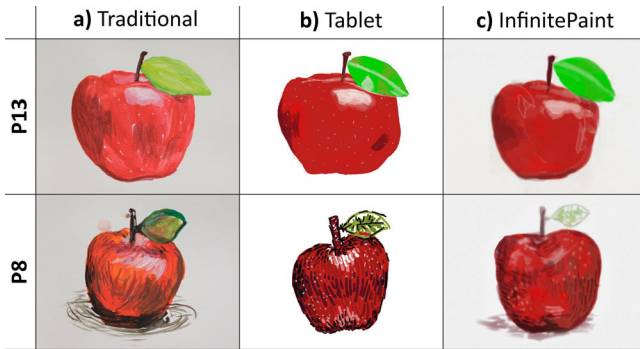
digital conditions of this block, participants could pick a color as well as adjust its brightness and opacity. Additionally, they had access to the eraser tool. The experimenter assisted the participant with the shifting whenever needed. Participants filled out a post-questionnaire after each condition with questions specific to our experiment (see *Appendix A*) as well as a standard User Experience Questionnaire (UEQ) [39].

Participants had 10 minutes for each condition. Before starting a condition, they had a few minutes to familiarize themselves and practice with the medium or interface. After all three conditions were finished, the experimenter conducted a short semi-structured interview (around 5 minutes) to gather qualitative feedback based on observations during the tasks. Overall, the first block typically lasted around 60 minutes including filling out post-questionnaires and the semi-structured interview at the end. Figure 5 shows examples of apples that participants painted in this first block. All 42 paintings of this block can be found in the supplementary materials.

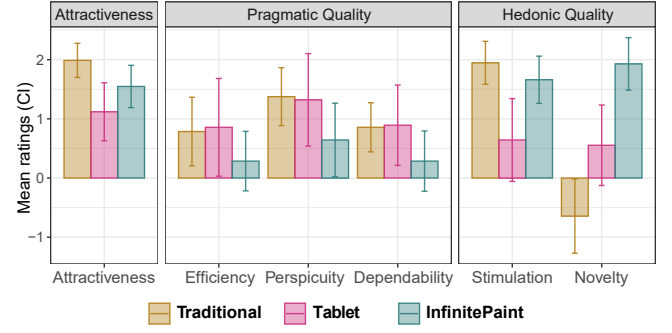
**4.4.2 Block 2.** After the post-interview of the first block concluded, we gave participants the opportunity to paint an object of their choice. We displayed a web browser in front of them in VR so they could search for a reference image of their chosen object. Participants then freely painted their motif while expressing more thoughts. Depending on their progress, we unlocked more techniques and tools of our prototype (undo, layers, smearing strokes, using special brushes and more). At the end, we also let participants informally try out the screen version without VR (as described in *subsection 3.2.1*) while they expressed their thoughts about the two versions in comparison.

The free-painting block was purely for additional qualitative feedback and lasted between 20 and 50 minutes, depending on the complexity of the motif and the amount of time participants wanted to spend finishing their painting.

**4.4.3 End of session.** After both blocks, the participant received a small gratitude and was dismissed. Overall, a session lasted anywhere between 90 and 120 minutes including filling out consent forms, pre-questionnaires and all post-questionnaires, as well as running the interview. The large variation of duration was mostly due to the flexible time span of the second block.



**Figure 5: Example paintings from the first block of our evaluation. The figure shows paintings of each condition of two example participants with different painting styles.**



**Figure 6: UEQ mean ratings per scale [39]. The error bars represent the confidence intervals (95%). Attractiveness is a pure valence dimension, pragmatic qualities are goal-directed aspects, and Hedonic quality refers to non goal-directed criteria such as fun-of-use or aesthetics [39].**

## 4.5 Quantitative results

For each variable, the participant was considered as a random factor and the condition as a within-subject factor. In this section, we report the most important results of the UEQ as well as the experiment-specific post-condition questionnaire. The plots of all subjective ratings can be found in the supplemental material.

**4.5.1 User Experience Questionnaire (UEQ).** The User Experience Questionnaire [39] is a set of 26 items, divided into 6 scales: Attractiveness (overall impression), Efficiency (no unnecessary effort), Perspicuity (easy to learn), Dependability (controllable), Stimulation (exciting, motivating) and Novelty (innovative, creative, interesting). Each item is rated on a seven-stage scale, e.g. from ‘annoying’ to ‘enjoyable’, or from ‘dull’ to ‘creative’. We analyzed the UEQ scales using repeated measures ANOVA. The normality of the residuals was verified for each scale (all  $p > .05$  with Shapiro-Wilk’s normality test). When the sphericity assumption was violated (Mauchly’s sphericity test), the degrees of freedom were corrected using the Greenhouse-Geisser and Huynh-Feldt’s method. We performed post-hoc tests (Holm-Bonferroni adjustment) to compare the conditions pairwise and report the effect sizes using  $\eta_p^2$ . Figure 6 illustrates participants’ self reported measures from the UEQ. The analysis showed a main effect on Stimulation [ $F_{1,13} = 8.48, p < .01, \eta_p^2 = .30$ ] and Novelty [ $F_{2,13} = 22.87, p < .001, \eta_p^2 = .53$ ]. Overall, participants rated INFINITEPAINT as more stimulating than TABLET ( $p < .05$ ), and INFINITEPAINT as more novel than both TRADITIONAL ( $p < .001$ ) and TABLET ( $p < .01$ ). Regarding results not involving INFINITEPAINT, the analysis also showed a main effect on Attractiveness [ $F_{1,13} = 4.67, p = .02, \eta_p^2 = .23$ ]. TABLET was rated as more novel than TRADITIONAL ( $p = .04$ ), but less attractive and stimulating than TRADITIONAL ( $p = .02$  and  $p = .01$ , respectively).

**4.5.2 Experiment-specific post-questionnaire.** For the Likert-scale items, we used Friedman’s test. We performed pairwise comparisons using Conover’s all-pairs rank tests with Holm-Bonferroni adjusted p-values and report the effect sizes using Kendall’s  $W$ . The results of our post-condition questionnaire with questions that are specific to our prototype are as follows: we found a main effect on Q5 (“It felt like painting with a real brush on a real canvas”)



**Figure 7: Example paintings from the free-painting block of our evaluation. By this stage of the study, participants used InfinitePaint for the second time and had access to functionalities like undo.**

$[\chi^2_2 = 22.19, p < .001, W = .79]$ , Q6 (“I felt like I was limited by the interface or medium”)  $[\chi^2_2 = 7.72, p = .02, W = .28]$ , and Q7 (“The brush or device felt good to hold and use”)  $[\chi^2_2 = 6.73, p = .03, W = .24]$ . Participants felt more like they were painting with a real brush on a canvas with INFINITEPAINT than with TABLET ( $p = .01$ ). Predictably, we found a similar effect for the TRADITIONAL medium compared to the TABLET interface ( $p < .001$ ). Participants had a better sense of where their hands were during the TRADITIONAL condition than during the TABLET condition ( $p = .03$ ).

## 4.6 Qualitative results

This section summarizes the comments from participants based on the comment field in the questionnaires, the semi-structured interviews as well as additional thoughts during the free-painting block (also see Figure 7 for some example paintings from the free-painting block). During the semi-structured post-interview, common comments were repeated by multiple participants, which gave us a general idea of the participants’ feelings about InfinitePaint.

**4.6.1 Appearance of strokes.** We received many positive comments about the appearance of the strokes—since they are textured from the camera input, certain effects that would be difficult to simulate (such as dry brush) were captured by our system. P12 commented that “the digital strokes were really beautiful”, and P3 said “the fact it captures all the brush stroke textures is just so cool”. Additionally, with the approach of always shifting to dry parts of the canvas, P9 mentioned that it was easier to do details in INFINITEPAINT: “Using small brush for tiny details is much harder on real watercolor, because you have to wait until it’s 100% dry”.

Around half (8) of participants wished for some form of color blending from different strokes into one another, as well as a possibility for blending colors more easily to make smooth gradients. Advanced features such as the blur tool and automatic bleeding were not provided to the participants during the study to keep the tool set minimal. We will discuss those tools in *subsection 5.1*.

**4.6.2 Brush versus pen.** Although participants noted that they had greater control in the TABLET condition (often due to the rigidity of the pen in comparison to the much softer brushes), the vast majority preferred the sensory feel and haptics of INFINITEPAINT.

P9 noted that the “interaction between physical and digital was far more tangible”, and that it was “much more sensual and tangible with the brush... I felt more connected with the canvas”. P3 said that it was “much nicer to use the brushes [because you get] interesting shapes and physical enjoyment from using brushes compared to hard rigid [styli]”. P16 wrote that “even though the pen is responsive, the brush is more natural”. Additionally, the unpredictability of watercolor was also present in INFINITEPAINT—despite the greater control of the stylus, P11 commented “the unpredictability of the brush I really like, unlike with the graphics tablet where you paint and it just goes where [the stylus] was”. P10 (a professional artist with VR experience) said “That’s what I often miss in virtual reality or augmented reality, people don’t experiment enough with physical materials [and there are] no haptics... [the brushes were] quite a sensual experience”. P9 additionally noted that “the sound, the friction of the brush definitely added value”. P5 felt that “it doesn’t have to be watercolor, it can be its own thing”, implying that InfinitePaint is not necessarily bound to a specific existing type of painting or painting styles.

**4.6.3 Limitations identified by participants.** Participants mentioned shifting universally as a limitation, where participants’ feelings towards it ranged from vague inconvenience (P12 only mentioned it when asked specifically about shifting) to confusion, irritation (P4 said it “is always confusing”, and it happens in “no other medium”), and immersion-breaking (P4). The experimenter assisted the participants with the shifting process, adding a potentially disruptive layer of communication. For the study, we kept the shifting approach simple (simply moving from quadrant to quadrant when pressing a button on the gamepad). We are confident that more subtle shifting approaches can alleviate this main limitation without breaking the immersion in the future.

Another limitation mentioned by 5 out of the 14 participants was depth perception. Since the camera feed is both a 2D projection as well as unwrapped from a slightly different angle compared to the user, these participants felt it was difficult to discern how far the brush was from the canvas. Although the majority of participants noticed this difference, most of them acclimated to it quickly. One reason that some participants found this more irksome than others is the position that some participants sat (or stood) in when painting.

Those participants looking from a lower position close to the canvas may have found the 2D projection more odd, whereas those looking directly down at the canvas may have found the perspective to match fairly well with that of the camera.

Six participants mentioned the UI as a limitation (of both the TABLET and INFINITEPAINT) since we provided only the option to change the colors digitally (i.e. adjust opacity and brightness) rather than provide an option to mix the colors in a neutral area before using them (as in the TRADITIONAL condition). P11 said that they “like to use different hues rather than brightness” to paint, which was not supported by our interface, and that the color selection left them “feeling unsatisfied”. While the color picker and color blending is orthogonal to our approach, providing better color picking and mixing capabilities [60, 65] is certainly an important aspect for future work.

**4.6.4 Learning curve.** Unlike with the TABLET, most participants noted that there was a steep learning curve with INFINITEPAINT. This could be because the depth perception with the brush took a little while to get used to, whereas drawing with a pen is more immediately intuitive. However, all participants felt they were a lot better by the end of the 10 minutes. P11 noted “I was definitely happier with the brush strokes I made in the end than those at the start”. Furthermore, in Block 2, the participants had yet more time to get used to the system, and there was a marked increase in satisfaction by the end, with P9 (“occasional small art projects”, ink drawer) mentioning “with a bit more practice, I could be as good with [InfinitePaint] as with actual watercolors”.

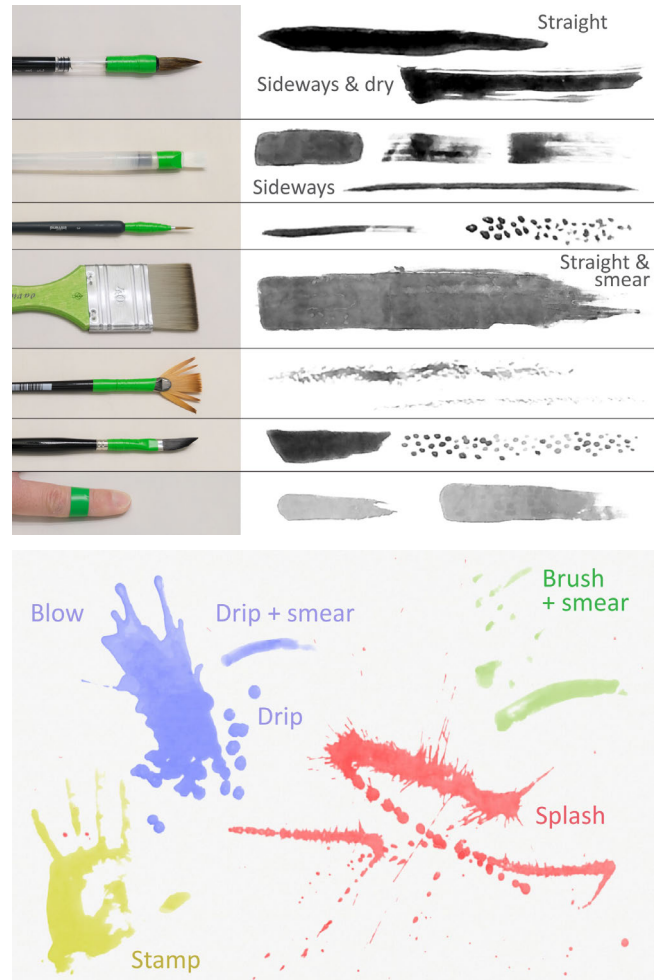
**4.6.5 Screen versus VR.** Despite some negative feedback about the resolution of the VR device and neck strain as well as one participant reporting mild symptoms of cybersickness, the majority of participants (10 out of 14) preferred the VR-version of the interface compared to using the system with a screen in front of them.

The weight of the VR device is a particular problem in our use-case, since many of the participants painted with their head looking down and close to the canvas. Two of the participants (P6 and P8) said that the weight of the device was a problem (and was the reason they preferred the screen version). The resolution of the headset was mentioned by the other 2 of the participants (P3 and P7) as their reason for preferring the screen version of the interface. Since small details were not sufficiently clear in the headset from far away, the participants were forced to move uncomfortably close to the canvas in order to see them properly as soon as they wanted to add very fine details.

From the participants who preferred the VR-version of the system, the main reasons given were that it was more difficult to locate their hand (especially after shifting the strokes) when looking at the screen. Additionally, some participants felt that there was a disconnect between where they were drawing on the real canvas compared to where they were looking, resulting in worse control compared to VR. Even though we do not have quantitative data to confirm our observation with those two variations, we could see a strong tendency of participants preferring VR, although many mentioned that they could also get used to the screen version. Our approach supports both versions and the choice is therefore up to the end-user. Individual preferences can potentially change after longer periods of accustomization and better hardware.

## 5 TOOLS AND ADVANCED TECHNIQUES

At its core, our approach supports painting strokes with an arbitrary physical brush (Figure 8 top), which is also what we investigated in our user study. However, due to how our capture method works, there are advanced techniques emerging from the concept without them being specifically implemented. More concretely, since we track the strokes on the physical paper, we can support use cases that are hard or even impossible to achieve with brush tracking alone, as it involves manipulating the water itself (Figure 8 bottom). For instance, users can use their finger to smear the water shortly after it was applied (Figure 8 green). Furthermore, the brush does not need to actually touch the paper—shaking the brush to splash water onto the paper works equally well and yields splash-effects in the painting (Figure 8 red). This technique was also employed (with a more subtle execution) for the pink particles around the



**Figure 8: Showcase of basic techniques and tools as well as advanced techniques, which are implicitly supported by InfinitePaint. Top: Different strokes or spots made with different brushes and usages. Bottom: Dripping, Blowing, Splashing, Smearing and Stamping.**



**Figure 9: InfinitePaint example paintings created after the study. The blossom tree branches were painted by Supraja Sridhara. The sword was painted by Edouard Angebault. The rest was painted by one of the authors (Andreas Fender).**

flowers in Figure 9. Dripping water on the paper achieves a similar (though less directional) effect and can be combined with smearing. Related to this, a common technique in Sumi-e is to apply a lot of water and blow the ink to achieve specific directional gradient effects (Figure 8 blue). Lastly, the water can also be applied with objects or tools other than brushes, e.g., by wetting objects or hands to use them as stamps (Figure 8 yellow).

## 5.1 Digital capabilities

As all the strokes are digitized, there is an opportunity to apply any number of purely digital techniques to an artwork and to enable

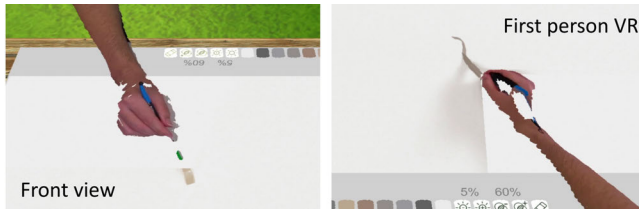
digital functionalities. Simple features such as undo/redo are common in digital painting making it easy to correct mistakes. Similarly, copy/paste and deletion can be useful. More advanced digital capabilities including individual stroke manipulation after drawing are also possible (scaling, translating, rotating, warping). InfinitePaint allows to work in layers, for instance to paint the foreground first and then the background—or to adjust the background without painting over the foreground. Combining different art styles in the same image is possible as well. Concretely, by increasing the opacity, the strokes appear more cartoonish (e.g., the sword in Figure 9), whereas by capturing more of the stroke artifacts at a much lower opacity, the appearance is more realistic (e.g., the mug in Figure 1 c) or more watercolor-like (e.g., the blossom tree branches in Figure 9). To blend already painted strokes, we implemented a simple Gaussian blur tool. Instead of applying a virtual color, the tool applies a dynamic kernel masked by the painted stroke. This facilitates subtle shading as in the painting of the fighter in Figure 9. A demonstration of the blur tool can be found in the first part of Video Figure B from the supplemental material.

**5.1.1 Rectangles versus triangulation.** By default, strokes are simply rendered as textured rectangles. However, we also implemented a ‘vectorization’ mode, where we create triangulations of the detected strokes. This enables more manipulations like changing the stroke thickness after the strokes have been painted. We used an open-source implementation of Sloan’s Algorithm [61, 62] for Constrained Delaunay Triangulation [55] and additionally remove holes. We use OpenCV’s contour detection on the threshold image to obtain the strokes’ vertices. The resulting triangulations can be exported as meshes to do manipulations in other applications. The second part of Video Figure B contains an example that showcases exporting the triangulated strokes to Blender and animating them.

**5.1.2 Texture-painting on virtual 3D objects.** With our approach, we are not limited to virtual canvases that are 2D planes [58]. Orthogonal to the core principle, all painted strokes can also be projected onto a virtual 3D object. This means that our approach enables the use of traditional art including its tactile sensations for a task that is conventionally fully digital. A video example of texture-painting on a virtual 3D object can be seen in the third part of Video Figure B.

## 6 DISCUSSION AND FUTURE WORK

The user study results largely corroborate that InfinitePaint outperforms a drawing tablet in Hedonic qualities (stimulation and novelty). However, a tablet is likely better on the Pragmatic front (including on metrics such as efficiency, speed, and easy to learn). Participants felt like they had more control with a tablet, but also noted that control is not always a desirable characteristic (P11: “the unpredictability of the brush I really like”) leading to participants preferring the brush compared to the stylus. Overall, our results indicate that our approach can be complementary to drawing tablet input whenever Hedonic qualities are preferred over very high precision input. Hence, we position our approach in use cases, which are about artistic exploration and experience rather than full control. In the remainder of this section, we reflect on our prototype and provide a set of close design alternatives, which also form the base for future work.



**Figure 10: Alternative visual output of our system.** We initially reconstructed the users hand and masked the parts beyond the brush head below the hand and arm in the homography projection. Only strokes and the brush tip would be visible in the projection. However, informal pre-testing revealed that a high-quality projection is preferable over the live-reconstruction with the same camera.

### 6.1 Alternative prototype designs

With our research artifact, there are inherently many possible alternatives in the exact execution and its intricacies. Based on informally testing with volunteers and iterating, we arrived at the prototype as described in this paper with all its design decisions and parameters. While not exhaustive, in this subsection, we describe the most important alternatives for our approach and prototype in order to provide a design rationale for our work and position it in the space of possible instances.

We initially used the Azure Kinect camera of the apparatus to create a live-reconstruction of the user’s hand (Figure 10). Combined with tracking the brush head at all times, users would see their hands in 3D while we masked out everything below the hands and arms. The idea was that only the brush tip and strokes are projected as a flat image. Informal testing revealed that the benefit of seeing the hand in 3D is marginal compared to potential issues arising from this approach. The reconstruction has a relatively low resolution and there are visual inconsistencies between the 3D and 2D parts (even after calibration). Furthermore, users have different grip postures, making it challenging to track the brush at all times with a single camera. In the end, we opted for the two-dimensional, but consistent rendering mode (e.g., Figure 1 b), which users generally accepted and got used to as also indicated in the majority of the qualitative feedback of our study. However, if multiple high-performance cameras are available, more flexible tracking and real-time 3D reconstruction without gaps might still be a viable alternative for our approach.

During the design phase, we long considered keeping the virtual painting stationary and instead moving the projection (including hands and real brush) whenever the artist wants to paint on top of existing strokes that have not dried yet. Since users are situated in VR, rendering the hands with a slight offset is acceptable or potentially even unnoticeable as revealed in haptic retargeting research [4, 13]. Especially since users need to repeatedly move the brush between the color picker at the bottom and the painting, there is potential for warping the movement instead of moving the virtual painting—especially when combined with aforementioned 3D reconstruction—so as to increase the sense of immersion. However, to reduce the risk of confounds in the study and to keep the amount of system parameters low, we opted for simply moving the virtual

canvas instead while keeping the hands world-anchored, providing the artist full control and awareness. Furthermore, painters who are proficient in using a brush (with potentially increased awareness of hand motions) might also have a strong sense of proprioception during the painting task, which could potentially make the warping a hindrance. With this trade-off between immersion and control, there is much potential for a dedicated investigation for haptic retargeting in painting in the future.

### 6.2 Combination with simulation

For the basic functionalities of our prototype, it is not necessary to simulate the behavior of water and paint on a canvas. However, our approach does not prohibit the simulation of additional effects. For instance, there are watercolor techniques that are not inherently supported by our approach in its most basic form. More concretely, wet-on-wet painting (applying a layer of water first and then applying color to distribute it evenly) would not work currently, because water instantly turns the canvas black. However, by combining this with a watercolor simulation, the same effect can still be achieved while retaining the tactile properties and without requiring precise brush tracking. Concretely, the user could simply select ‘water’ instead of a color and any strokes would just be registered as virtual water layer. By shifting the virtual canvas and selecting a virtual color, the behavior of paint on water could then be simulated—with the advantage that the virtual water does not unintentionally ‘evaporate’ over time. To enable real-time feedback, future approaches will additionally need to segment the stroke while it is painted, e.g., by incorporating the brush tracking during the painting process. This would also additionally make it possible incorporate the movement direction of the brush into the simulation while the stroke is being painted. Such hybrid capture and simulation approaches have the potential of being a future research direction.

## 7 CONCLUSION

We presented the InfinitePaint concept and prototype. Our approach enables the capabilities of digital art, while at the same time preserving the passive haptic sensations of painting with a wet brush on paper in traditional art media. By digitizing wet brush strokes before they evaporate over time, the user can paint infinitely on the same real canvas without using up art materials and with digital functions like undo or specialized effects. The design allows for a low-cost setup without specialized hardware and without the need to precisely track the brush head. We conducted an evaluation with artists. The results indicate that users that practice traditional media found much enjoyment and expression with our prototype compared to a drawing tablet. Our approach is expandable as it has the potential to support many additional digital effects that complement the expressive brush input. With this work, we hope to inspire future research that combines traditional and digital painting.

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## A APPENDIX: POST-CONDITION QUESTIONNAIRE

The questionnaire with study-specific questions was given to participants after each condition in the first block. Each question was rated on a Likert-scale ranging from 1 (strongly disagree) to 7 (strongly agree). The results for this questionnaire are primarily discussed in *subsubsection 4.5.2*. The plots of all subjective ratings can be found in the supplemental material.

- Q1 I felt the interface or medium was easy to use
- Q2 I felt like I was in control of the brush
- Q3 I felt like the strokes I painted looked as I intended
- Q4 I felt like I was painting fast, i.e., I finished the painting quickly
- Q5 It felt like painting with a real brush on a real canvas
- Q6 I felt like I was limited by the interface or medium
- Q7 The brush or device felt good to hold and use
- Q8 Applying color to the canvas (virtual/real) felt good
- Q9 It was easy to pick the color that I wanted
- Q10 I always knew where my hands were
- Q11 I am satisfied with the resulting painting
- Q12 I could see myself using this interface or medium in the future