Painting an Apple with an Apple: A Tangible Tabletop Interface for Painting with Physical Objects

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We introduce UnicrePaint, a digital painting system that allows the user to paint with physical objects by acquiring three parameters from the interacting object: the form, the color pattern and the contact pressure. The design of the system is motivated by a hypothesis that integrating direct input from physical objects with digital painting offers unique creative experiences to the user. A major technical challenge in implementing UnicrePaint is to resolve the conflict between input and output, i.e., to be able to capture the form and color pattern of contacting objects from a camera, while at the same time be able to present the captured data using a projector. We present a solution for this problem. We implemented a prototype and carried out a user study with fifteen novice users. Additionally, five professional users with art-related backgrounds participated in a user study to obtain insights into how professionals might view our system. The results show that UnicrePaint offers unique experiences with painting in a creative manner. Also, its potentials beyond mere artwork are suggested.

CCS Concepts: • **Human-centered computing → Ubiquitous and mobile computing**; *Graphics input devices*;

Additional Key Words and Phrases: Digital painting system; Creativity support system; Tangible User Interfaces (TUI); Tabletop interface; Frustrated Total Internal Reflection (FTIR)

ACM Reference Format:
Kaori Fujinami, Mami Kosaka, and Bipin Indurkhya. 2018. Painting an Apple with an Apple: A Tangible Tabletop Interface for Painting with Physical Objects. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 2, 4, Article 162 (December 2018), 22 pages. https://doi.org/10.1145/3287040

1 INTRODUCTION

The advancement of computer graphic simulations and input technologies has enabled high fidelity replication of traditional artworks in digital manners such as watercolor painting [4, 35, 36], airbrush painting [30], oil painting [2], and sand animation [21, 34]. Even the colors of physical objects can be captured [16, 28]. Not only the replication, but also new expressions that benefit from digital information have been explored, such as presenting animation and video captured during artwork activities [21, 28]. Furthermore, the advancement in haptic technologies has made it possible to design systems that give feedback to the user on the shape and texture of the painting surface [1, 23, 33].

Meanwhile, painting-like activities in the real world include activities that utilize, not only dedicated tools such as pen and paintbrush, but also various everyday objects as material for expression. The latter examples

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2474-9567/2018/12-ART162 $15.00
https://doi.org/10.1145/3287040

include rubbing various roadside pebbles, stamping with pieces of inked-up ingredients [12], dying fabric and paper with the color of flowers and leaves [8], etc. People not only just use the objects as they are, but also cut, prune, and entrench the objects to obtain favorite expression. Such activities that deal with the material in the real world have attracted adults as well as children. We aim to expand the experience of physical object-based painting to the digital world and design and implement a system called UnicrePaint. In UnicrePaint, people can use physical objects as painting tools (Fig. 1). The form and color pattern of the object in contact with the painting surface is captured and presented at the contact position in real time; a trace of the appearance is drawn as the object is moved; the pressure applied to the surface during painting is also reflected in the presentation. Our aim is to allow the user to transfer their experiences with pressing stamps on drawing paper or rubbing roadside objects on the ground, for example, into digital painting. In digital painting systems, a key benefit is the ease of editing the artwork. The user can easily undo/redo recent painting activities, copy/paste pieces of work, erase a particular area, and so on.

This approach differs from the ones that aim to replicate traditional artworks in digital manners in that it actually uses physical objects in digital painting. Using physical objects as painting tools have already been proposed in the context of tangible user interfaces [17], in which various expressions were observed, the users had enjoyable experiences, and the trial-and-error process allowed the children to facilitate creativity [10, 28]. Particularly, I/O Brush [28] is a closely related work to UnicrePaint, which transfers the appearance of an object via an augmented paintbrush, while a user of UnicrePaint can directly paint with dedicated objects. Also, in a previous study [22], a similar concept was presented, which only deals with the form of contact. In the design presented here, we extract two more parameters from the physical object during painting, namely the color pattern and the pressure applied to the input surface during painting. We believe that these three parameters will provide the users with unique creative digital painting experiences.

The design of our system is aimed at adult novice users, who will use the system for recreational purposes in dedicated places such as an art museum or a craft workshop. However, later we also consider the usability of this system for professional artists.

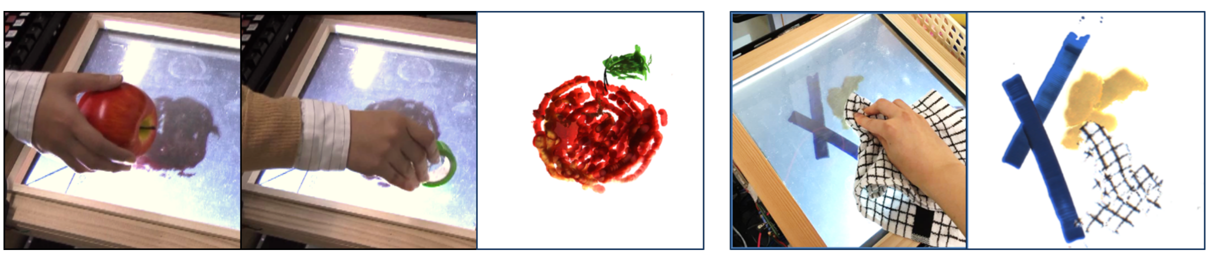


Fig. 1. Using UnicrePaint and some generated pictures

This paper makes the following three contributions:

- We introduce a new digital painting tool that leverages the form and the color pattern of an object contacting on a surface and the pressure applied to the surface through the object to provide unique, creative, and enjoyable experiences.
- We describe our implementation in terms of acquiring contact surface information and present it in a co-located and real-time manner. Particularly, a new technique called *selective capture* is proposed for capturing input from the user while projecting the rendering of the painted work at the same time in a cost-effective manner.

- We evaluated UnicrePaint with 15 novice users to determine whether the integration of direct input from physical objects with digital painting offers a unique creative experience. Also, five professional users with art-related backgrounds also evaluated UnicrePaint based on their experiences and knowledge of art media, in which comparison with I/O Brush (based on viewing a video of it) is carried out.

The rest of the paper is organized as follows. Related work is presented in Section 2, in which digitally augmented traditional painting activities and digital painting using physical objects are examined to clarify the uniqueness in the concept of UnicrePaint. Also, various methods of acquiring contact surface information are reviewed to show the technical challenges of UnicrePaint. The design and implementation of UnicrePaint is described in Section 3 with emphasis on extracting the three parameters of form, color pattern and applied pressure of contacting objects, while, at the same time, projecting the rendered output. Basic performance evaluation on the prototype system is also presented. Then, Section 4 describes a user study, followed by discussion in Section 5. Finally, Section 6 presents the conclusions.

2 RELATED WORK

2.1 Digital Replication of Physical Painting Activity

In this approach, traditional painting activities are augmented digitally by simulating the physical painting tools and the experience of painting with those dedicated tools (like paintbrushes, spatula, etc.) The aim is to provide the user with a virtual painting experience similar to real painting. In painting in a virtual world, haptic feedback is utilized to give the feeling of contact force between the tool and the painting surface. DAB [1] and MAI painting brush++ [33] simulate the contact force against the virtual painting surface by actuating the part held by the user. In contrast, an indirect approach is taken in FlexStroke [23], where the user can paint on a tablet using a special stylus, deforming its tip physically to generate various forms of contact such as ink brush, crayon, and oil brush.

In replicating particular painting activities such as air brush painting [30] and water painting [35, 36], tactile feedback is not necessarily required because real physical tools are utilized, except that the output is rendered on a digital canvas. Shilkrot, et al. developed an augmented airbrush system that uses a spray gun as input [30]. This spray gun does not spout real paint, but simulated paint is presented on the screen by a projector based on the position and the operation of the spray gun. IntuPaint [36] utilizes a special paint brush to provide the system with the position and the shape of the brush tip, while FluidPaint [35] allows the user to use a real paint brush under the condition that the brush is wet. The utilization of familiar tools allows users to easily adapt themselves to new digital painting activities.

2.2 Tools for Creating Digital Art using Physical Objects

Existing tools for creating artworks digitally depend on the use of a mouse and keyboard, which makes the task of creating artifacts difficult for beginners. In recent years, several tangible user interfaces [17] have been developed to support creative activities digitally. For example, I/O Brush [28] enhances the creativity of digital painting and allows the users to create images as if they were painting with a paintbrush and paint. FingerDraw is [16] also based on the *color palette* interaction model. By contrast, a system for painting directly with physical objects is presented in a previous study [22]. However, in this system, only the contact shape is captured, and the color needs to be selected from a given list. The contact pressure is not captured. kidCAD [10] also allows young users to directly utilize physical objects, capture their shapes, and edit the captured information. This system utilizes a gel-based surface deformation sensing technology called deForm [11].

These studies demonstrate that the utilization of physical objects as tools for generating artwork encourages users' creativity. The color palette interaction model allows the user to use large or heavy objects, something which is not supported by the direct painting model. UnicrePaint adapts a direct painting model to incorporate tangibility of painting with physical objects.

In evaluating these systems, the process of creation as well as deliverables and interview results from the participants are used. Creativity is validated by considering the details of the participants' behavior during the experiment [26, 28], and in-depth analyses of the videotaped activities [10].

2.3 Acquisition of Contact Surface Information

UnicrePaint captures the shape and the color pattern of the contact area between an object and the input panel as if the object is being scanned. The pressure applied to the panel during painting is also captured.

2.3.1 Detecting Form of Contact Surface. In recent years, optical multi-touch sensing technologies have been developed to utilize the information from contact surfaces of fingers and objects [7, 14, 18, 20, 24, 32]. These use infra-red (IR) light as it is robust against ambient light and is invisible to the user. The reflection of IR light from fingers and objects, except for the transmitted light from the fingers [7], is captured by IR-sensitive devices. Among these, Han's system forms the basis of our UnicrePaint technology, which utilizes the principle of frustrated total internal reflection (FTIR) of IR light, because of the ease of development and its cost effectiveness [14]. As the contact surface is captured by an IR camera, the color information is not obtained; however, the contact shape information, i.e., the gray level of pixels, is utilized in UnicrePaint as described later.

2.3.2 Acquisition of Color Pattern of Contact Surface. Many systems use an RGB camera to capture the color pattern of objects. For example, in I/O brush, a camera is embedded inside the paintbrush-like device to capture the color pattern of objects where the paintbrush is placed [28]. Similarly, in FingerDraw [16], a camera is attached on the index finger of the user to capture the color of pointed objects. In all these cases, the color patterns of the objects are captured by portable devices and used like paint. However, in our design of UnicrePaint, the user can directly apply the object of interest on a special input surface, and the captured shape and color pattern are presented on the same surface in real time. This creates a conflict between the input and output devices (video camera and projector) trying to use the same surface at the same time.

A straightforward approach to solve this problem is to alternate between the projection and the capture at a high rate (e.g. 60-70 Hz) so that it is imperceptible to the human eye. Switchable diffusers are used as a solution to this problem [13], which are based on the technique of changing the optical properties of the projection screen containing liquid crystal molecules from transparent to opaque and back. The opaque surface is used for projection, while the surface is turned transparent for capturing. The switchable diffuser can be attached to the projector to work as a shutter for the projector's light [19]. In either approach, the switching between the input and the output modes needs to be timed precisely. In the worst case, the camera ends up capturing the opaque surface, and the color pattern is not obtained. Additionally, the effect of switching extends over the entire surface, resulting in flicker. To overcome such problems, the system needs special synchronization circuits and a high-performance image processing unit, in addition to a high-speed switchable diffuser and its driving circuits, all of which add to the cost. As shown in Section 3.2, in UnicrePaint, we propose *selective capture* as a solution without sacrificing the usability and cost effectiveness.

2.3.3 Measuring Pressure Applied to Input Surface. For capturing the pressure applied to the surface, IMPAD uses a pressure-sensitive surface implemented with an array of force-sensitive resistors [25]. This approach needs to cover the entire surface with the sensors, although it allows fine-grained and multiple measurements at a time. This design does not allow sensing the form of the contact area at the same time because it requires clear visibility behind the input panel. Another approach to capturing pressure is using IR-based optical multi-touch sensing [15], in which dedicated marker pads are attached to each object, and the number of contact points and the contact area are transformed into the pressure level. This approach seems to fulfill the requirements for contact form sensing in UnicrePaint; however, the necessity of having pads attached to the objects requires prior preparation and prevents objects from being used extemporaneously. A third approach is to install load cells at each of the four corners of the input panel to measure the position and the pressure of the applied object based on the force distribution [29]. This addresses the problem of projecting the output on the panel while capturing the input from it at the same time. In the implementation of UnicrePaint, we adapt this load sensing approach with some simplifications.

3 DESIGN AND IMPLEMENTATION OF UNICREPAINT

As specified in Section 1, the target group is adult novice users. Shneiderman argues that novice users, in general, require a low threshold of entry into the creative domain to sustain engagement with a tool because of their lack of confidence, skill, or motivation for using the tool [31]. Therefore, we considered the ease of use as the main design goal and tried to incorporate as much physical world experience of paint-like activities as possible. In the physical world, drawing with an object while pressing on it strongly often transfers the color of the object. The contact pressure also makes a difference in the density of the trace. Furthermore, the result (trace) of drawing (output) appears on the same surface on which the user is drawing — there is no delay from the input to the output. UnicrePaint is designed to realize all these characteristics in a virtual interface. In addition, fear of failure sometimes leads to disengaging with a creative tool as pointed by Davis, et al. [5]. So, we introduce a set of functionalities, as is often provided in graphical user interfaces (GUIs), to recover from undesired situations.

3.1 Major Functional Components

When painting with real objects, color, appearance and pressure play a major role. So, we chose to focus on these three parameters in the design of UnicrePaint to make the user feel as if she or he were painting with physical objects on a physical canvas, while offering digital painting experiences.

- Capturing the color pattern of the object contact area, and displaying it to the user in real time.
- Measuring the pressure applied by the object for painting and displaying it to the user in real time.
- Providing usual functionalities like undo-redo, color palette, etc. that are associated with digital painting.

Fig. 2 shows the configuration of UnicrePaint, which consists of an Input-Output (IO) panel, an Infrared (IR) camera, an RGB camera, a video projector, and a personal computer (PC) with a keyboard and a mouse. The IO panel acts as a canvas that provides real-time and co-located feedback for painting activities. The information about the user's activities related to painting is given to the system, while the painted result is presented to the user. The form and the color pattern of the contact area is captured by a combination of IR and RGB cameras placed under the panel. The pressure applied by the user for painting is measured by force sensors installed on each of the four corners of the panel. A video projector presents the current state of the painting from underneath the panel. A transparent rear-projection screen is attached to the IO panel so that images can be captured while projecting feedback images on it. We take the rear-projection approach because the front-projection approach with a projector installed above the table degrades the user experience due to occlusion from the user's body as noted by Izadi, et al [18]. In the rear-projection approach, the current state of the painting is always visible, which is critical to provide the user with a realistic painting experience. The keyboard is used for editing the image.

3.2 Capturing and Displaying the Color Pattern of the Contact Area

The color pattern of the contact area is captured by an RGB camera, while the current state of the painting is projected on the same surface. This creates a problem in that the projected image representing the already painted area may overlap with the image to be captured by the camera. Resolving this interference of output and input was a unique design challenge for UnicrePaint.

As discussed in Section 2.3.2, the switchable diffuser approach can be a solution; however, it increases the cost due to special electronic components and a switching controller. Instead, we investigated a software-based solution called the *selective capture* method, in which, instead of switching between projection and capture, just

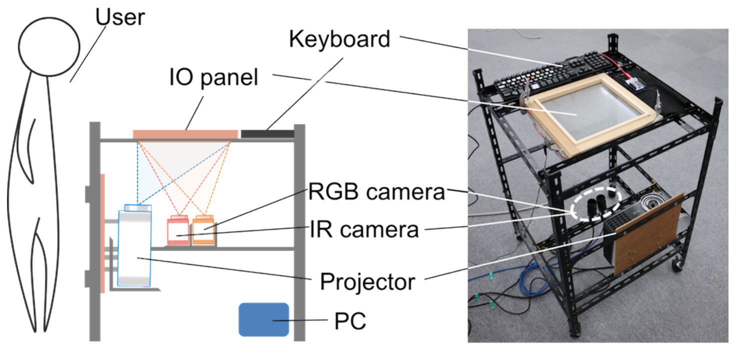


Fig. 2. System configuration

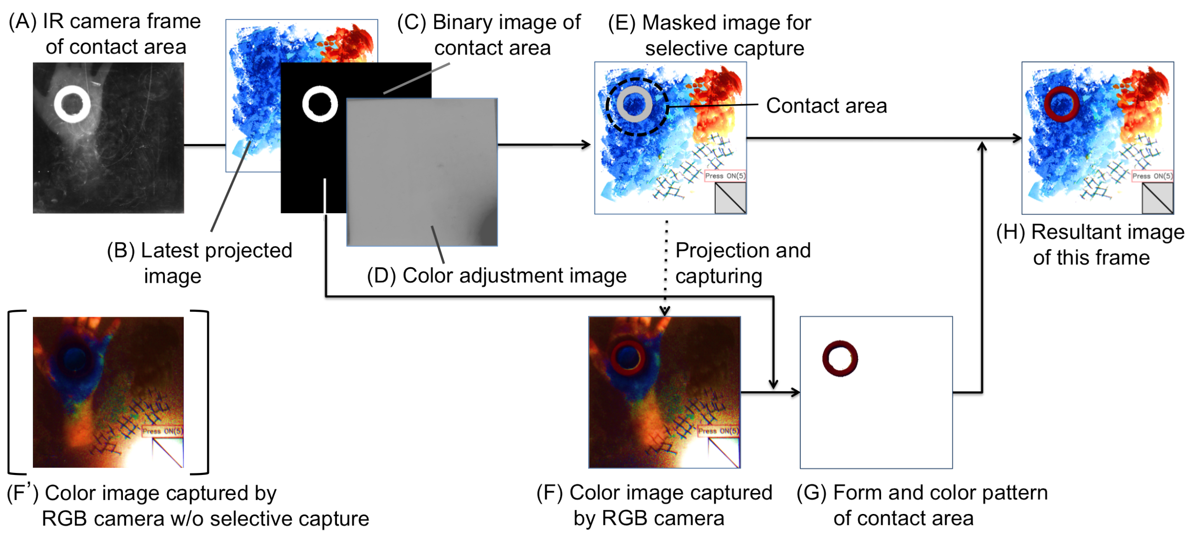


Fig. 3. Basic flow of selective capture and display

the contact area is rendered transparent so that the camera can capture the form of the input object pressing against it without interference from the projected image. De Charette *et al.* [6] present a similar concept of selective projection, where headlights of a vehicle are controlled to illuminate only the area around particles (like rain drops and snowflakes) to improve driver visibility. This method relies on the physics of precipitation and utilizes a model to predict the particle positions in the next time step for generating updated image for projection (illumination). However, for our situation, the trajectory of the painting object is not predictable based on a model, so the problem is more challenging.

Fig. 3 illustrates the basic architecture of selective capture. In the situation shown here, a red vinyl tape is placed on the surface already painted blue. The processing consists of four stages. For each frame from the IR camera (A), a binary image (C) is extracted with a threshold to mask the latest projected image (B) with the contact area only. However, to compensate for the distribution of light from the projector lamp, and to increase the reproducibility of captured color, color adjustment image (D) is applied to the binary contact area image. The adjustment image is generated in the system calibration phase, where the brighter area close to the light source is converted to a lower intensity, and vice versa. Note that in (D), we assume that the projector's light source is located at the bottom-right corner. Once the masked image (E) is presented on the IO panel from the projector, the RGB camera captures the projected surface (F). Since the colored area in the latest frame is overwritten with the contact area, and the mask acts as flush light, the object's surface is clearly seen. For comparison, an image captured by the RGB camera without the masked image is presented (F'). The selective capture successfully shows the red circle of the vinyl tape in (F), while the contact surface is hardly seen from the painted color (blue) in (F').

The color image from the RGB camera (F) contains the form of the contacting object as well as the painted images from previous frames. To generate a new frame for projection, further processing is needed. Firstly, the binary image (C) is combined with the captured image, and the form and the color pattern of the contact area is extracted (G). Secondly, the masked image (E) is merged with the contact area image (G) to synthesize the resultant image (H). Finally, the image (H) is displayed to the user as a result of the painting activity in the last frame. In every frame of video presentation, the selective capture and display process is repeated from (A). For the entire duration that the object is on the panel, projection of an image for selective capture (E) and a resultant image of the frame (H) are alternatively projected. However, this is not perceived by the user because it happens under the object, and the visible area for the user does not change for camera capturing, which avoids the flicker problem that occurs in the switchable diffuser approach. If the object is moved faster than the duration (A) and (F), the selective capture fails to obtain an appropriate color pattern of the object, it results in an incorrect color pattern as shown in (F'). Additionally, a long processing delay makes the interval of IR capture too long, thereby making the trace of an object movement appear discrete. Therefore, a fast processing speed is crucial for reproducing the object color faithfully and providing continuous feedback for the painting activity. Note that the selective capture can process contacts with multiple objects at the same time because it does not recognize objects, but deals with an IR image with a certain level of threshold.

3.3 Measuring the Pressure Applied to the IO Panel and Its Display to the User

The intensity of painting is calculated from force sensors installed on the four corners of the IO panel. At first, we tried to reproduce the method proposed proposed by Schmidt *et al.* [29], which captures pressure at multiple points; however, we could not obtain enough precision. So, we took a simpler approach: the pressure applied to the entire panel is measured by averaging the four sensor readings, and the value is converted to what we refer to as the *intensity* of painting.

We designed the conversion function so that users can feel natural feedback when they press on the panel, as illustrated in Fig. 4. We separated the range of contact pressure into five classes (ex_weak, weak, normal, strong, and ex_strong) and specified different rules for them. The intensity difference for the weak and strong pressures changes linearly according to the pressure level, and is added to the original pixel values (Fig. 3 (G)) to obtain the final intensity. By contrast, in the normal range, the intensity difference is set to zero, and thus the original pixel values are used. This was empirically determined to avoid too much sensitivity to the contact pressure. As the strength of the contact pressure is subjective, a calibration phase is introduced for each user to determine the boundaries between the five classes: $f_1(w)$, $f_2(w, s)$, $f_3(w, s)$, and $f_4(w)$, where a user is requested to press the IO panel weakly and strongly in his/her own way. Here, w and s represent the levels with weak and strong pressures, respectively, and f_i are the functions of either weak or strong levels or both. If a user applies a pressure that is weaker (stronger) than w (s), the intensity differences are set to constant values.

To allow for different preferences, four types of visual feedback of the input pressure are provided by changing: 1) saturation in HSB color space, 2) saturation in HLS color space, 3) brightness, or 4) luminance. Additionally, two ways of increasing or decreasing the intensity of the four color elements in proportion to the change in

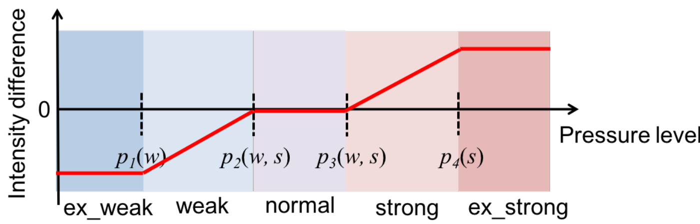
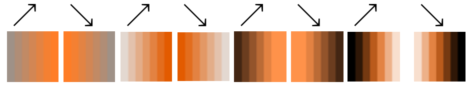


Fig. 4. Pressure level to intensity conversion function

pressure are provided. Thus, a total of eight patterns of visual feedback are available to the user. Table 1 shows some examples. Note that visual feedback is applied to the image representing the form of the contact area only, i.e., Fig. 3 (G).

Table 1. The arrow ↗ (↘) indicates that the value of the corresponding color element increases (decreases) as the pressure applied during painting is increased, as shown in the example. The intensity changes with 8-bit gradations.

Type	1	2	3	4	5	6	7	8
Element	SAT_{HSB}		SAT_{HLS}		BRI_{HSB}		LUM_{HLS}	
Direction	↗	↘	↗	↘	↗	↘	↗	↘
Example								

3.4 Editing and Processing Image

One advantage in digital painting is the ease of editing an image. In traditional non-digital painting, erasing an area or a line is difficult or even impossible. By contrast in digital painting, all painting processes are recorded, which makes such changes much easier. UnicrePaint offers minimal functionalities for image editing, which are: 1) scrolling back and forth through the recorded input (through sequence of contact-point pairs); 2) erasing a specific area with any objects (actually painting with default background color); and 3) clearing the entire screen. These functionalities allow the novice users to recover from undesired situations and facilitate trial-and-error processes, which would motivate them to engage with the system. Also, users can select a specific color from the color palette with 12 colors, rather than using the color pattern of the contact objects. In addition, a choice of 8 types of pressure-to-intensity conversion rules is provided. These are unique features of digitally augmented painting, i.e., the attributes are used in various ways once captured. All the functionalities are accessed via a keyboard connected to a PC.

3.5 System Configuration

The IO panel consists of an FTIR layer, a painting pressure detector, and a projection panel. The FTIR layer consists of a compliant surface (1 mm thickness), an acrylic panel (3 mm thickness), and IR LEDs (λ=830 nm). The compliant surface is used to facilitate the FTIR effect under pressure, e.g., pressing with an object. Choosing a compliant surface with appropriate hardness is important in the user experience, the robustness of the surface, and the quality of resultant pictures [22]. After numerous trials with different materials and hardness values, we used a material based on polyurethane gel, which was originally designed for vibration and shock absorption (Exseal Co., Hyper gel 50 [9]). The input and output area is a 30 cm square, and fourteen IR LEDs were installed at 2 cm intervals on each edge of the IO panel frame. To detect the pressure applied during painting, four pressure sensitive resistors (FSR) were installed on each corner of the IO panel between the acrylic and the projection panels, which were connected to the PC via an Arduino micro-controller. A rear projection film with 88% transparency was attached on the other acrylic panel to allow for capturing the color pattern of contact objects through the film. The application Fingerpaint Plus [32] also employs FTIR-based contact-point sensing and projection-based feedback with a rear projection screen, which is placed on the *top* of a silicone panel. However, this construction may prevent the input object from properly contacting the TIR-ed silicone layer, causing the application to fail to capture the form precisely. To allow a user to draw and paint with a physical object, input precision was incorporated in the design of UnicrePaint by installing the rear projection film *below* the FTIR layer.

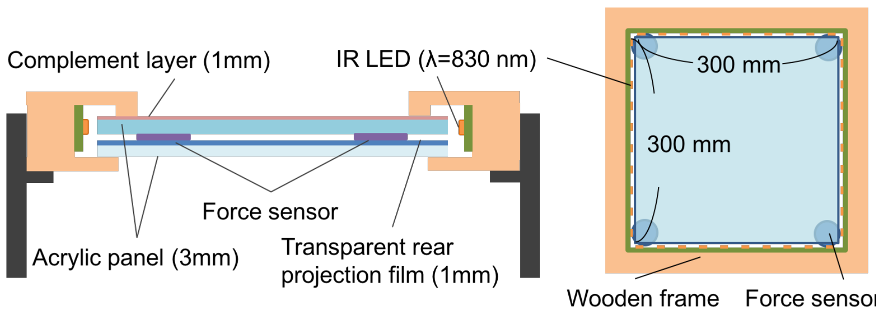


Fig. 5. Configuration of IO panel

Both software and hardware are configured to realize fluid interaction. RGB and IR cameras (PointGrey Flea3 1.3 Mpixels) operate at a frame rate of 120 Hz and transfer the captured data to a PC over USB 3.0. The software runs on a 4.0 GHz Intel Core i7-3600 CPU, running Windows 10 with 16 GB RAM. A graphics card with Radeon R9 370 with 4 GB RAM was utilized to accelerate image processing using OpenCV 3.1. The transparent API (T-API) in OpenCV allows the developer to use the GPU in the same manner as the CPU. Graphic rendering was accelerated by OpenGL. Note that the IR camera was actually implemented by attaching a bandpass filter (λ=820∼910 nm) to a monochrome camera to capture only the reflected IR light from the FTIR-based IO panel.

3.6 Basic System Performance

All these design choices allowed us to run the system at about 40 fps; that is, the time delay from capturing a new frame from the IR camera for contact area detection to generating the feedback image is 25 milliseconds. This speed was achieved largely because of GPU processing: the frame rate drastically degraded to about 7 fps when the image processing was carried out on the CPU only. The ability to present the rendered image in a continuous manner affects the user experience. By checking the display continuity against a moving object (a vinyl tape in this case) at different speeds visually, we confirmed that 4 cm/s is the upper limit for the painting speed. Regarding the input resolution, we verified that the lower limit on the thickness of an object to capture its trace by one pixel is 0.3 mm, so a mechanical pencil lead can be used. The reproducibility of color capture was evaluated by comparing the true color images of colored sheets and the captured ones visually. We confirmed that the brightness of the objects' colors affects the reproducibility, i.e., the middle level bright color was highly reproducible, while subtle and dark colors became darker and brighter, respectively, than the true colors. We built a prototype with these performance metrics and conducted a user-experience evaluation, which is presented in the next section.

4 USER STUDY: METHODOLOGY

A user study was carried out to determine whether the integration of direct input from physical objects with digital painting offers a unique creative experience. An additional objective of this user study was to understand the utility of the following features offered by UnicrePaint during painting activities: 1) co-located display of the captured form and the color pattern of an object, 2) feedback of the pressure applied by the object, and 3) editing and processing the captured information of objects. The experimental protocol was approved by the Institutional Review Board of Tokyo University of Agriculture and Technology.

4.1 Evaluating Creativity

We designed the system so that the experiences with the system could be creative. Though we all have some intuitive understanding of creativity as a conceptual and cognitive process, there is no common agreement in the research community as to how to define it or measure it, and a number of different approaches exist. For example, the Creativity Support Index (CSI) proposes six dimensions of creativity: exploration, expressiveness, immersion, enjoyment, results worth effort, and collaboration [3]. KidCAD [10] used three parameters: searching objects to be used (exploration), expression in works, and supporting many paths (diversity). The diversity of input methods was also used in SandCanvas [21], which included the degree of freedom in input gestures and the number of multiple solutions observed in a task. In addition, research on story creation by robot programming for children also regards various ways of using motion programming tools as creative [26]. In most cases, the heterogeneity and the freedom of operation and expression are considered as key elements of creativity, and, as found in CSI, they enhance the user experience with the system or the tool.

Based on the analysis of existing creativity metrics in related fields, we chose to focus on the following aspects of creativity in the integration of physical objects with digital painting because of their relevance to the design goals of UnicrePaint: 1) supporting trial-and-error (*exploration*), 2) *heterogeneity* of input objects and methods, and 3) sense of freedom of expression (*expressiveness*). We also consider *enjoyment* in using the system as evidence of creative experience.

4.2 Participants

Fifteen novice users (12 females and 3 males, labeled “A” to “O”) in their 20s (students and business people) participated in the experiment. They had no prior background in art and had never used UnicrePaint. They also did not have any preferred style of painting, though ten participants indicated that they were interested in painting. In addition, to obtain insights into how professionals might view our system, we also invited five users (4 females and 1 male, labeled “P” to “T”) — an art archive researcher, an art performer, a fashion designer, a photographer, and an illustrator — who have been working as professionals from 1-20 years. All but one user (the illustrator) finished undergraduate or graduate studies in art colleges. Each participant received JPY 2,000 (about US $18) for her or his participation.

4.3 Procedure

The experiment was carried out in three phases, which took about two hours. In the first phase, the experimental procedure was explained to the participants, followed by a tutorial of the system. Each participant tried out the eight patterns of the visual feedback of painting pressure, and chose their preferred one for a later phase. Throughout the tutorial, the participants were allowed to use any object with which to experiment and understand the functionalities and the operation of the system.

The second phase was free painting: each participant painted at least one picture. If a participant was not able to think of a motif for painting, the experimenter suggested topics such as preferred music or movies. The participants were allowed to choose colors of their painting from a palette of 12 colors as desired. This means that only the contact shape of the object was captured interactively in this mode. The painting process in this phase was video taped for later analysis.

The third phase was a semi-structured interview session. The novice users were asked six questions about creating artwork with physical objects (Q1-Q3) and the functionality and usability of the system (Q4-Q6). In regard to creativity, *exploration* is evaluated based on the answer to Q2 and the analysis of video-taped/logged painting activities. Note that Q2 is intended to understand the effect of *exploration,* if any, in the resultant artwork. *Heterogeneity* is analyzed by video-taped/logged painting activities. Finally, *expressiveness* is assessed by the answer to Q3 to Q6. *Enjoyment* in using the system is assessed by the answer to Q1 and the associated reasons.

Q1: Did you enjoy painting with objects? (5-point Likert scale)
Q2: How did the object-finding process affect the artwork?
Q3: How strongly did you feel that you were painting with the object in your hand? (5-point Likert scale)
Q4: Which objects were suitable for painting?
Q5: Which objects were unsuitable for painting?
Q6: Which visual feedback of pressure was most intuitive?

Instead of questions from Q1 to Q6, the participants in the professional group were asked questions about the possibility of UnicrePaint as a tool for professional artwork (Q7) and the difference between I/O Brush [28] and UnicrePaint as tangible painting tools (Q8). For the latter question, the participants were presented an online video of I/O Brush [27] to understand its functionalities and the resultant artworks. Then, they were asked to describe their thoughts regarding the differences in the user experiences. I/O Brush was chosen for comparison because we consider that the existence of an inherent painting tool is a key difference between them; a user of I/O Brush uses an augmented brush to transfer the properties of physical objects, while UnicrePaint allows a user to transfer the properties from target objects directly. In the latter section, we call the painting models of I/O Brush and UnicrePaint indirect and direct painting, respectively.

Q7: What kind of artwork is the system suitable for?
Q8: How different are these two types of physical-digital painting systems in terms of user experience?

4.4 Physical Objects

The participants could use a number of different objects for painting. We prepared 35 types of objects (Fig. 6), which were categorized into three groups based on their functionality: 1) Kitchenware: cup, sponge, imitation fruits, etc. 2) Stationery: pen, vinyl tape, scissors, etc. 3) Indoor objects: plastic ball, soft toys, postcards, etc. Additionally, the participants could bring their preferred objects, as well as use objects available in the laboratory.

5 RESULTS AND DISCUSSIONS

We present here the results of our user study. Section 5.1 discusses creativity offered by UnicrePaint based on the system logs, questionnaire survey and participant interviews. Section 5.2 focuses on the emotional aspect of *enjoyment* as a result of creative activities. Sections 5.3 and 5.4 discuss, respectively, potential applications and the uniqueness of UnicrePaint by comparing an augmented paintbrush approach, i.e., I/O Brush. Section 5.5 evaluates various issues related to the system usability. Finally, Section 5.6 summarizes the user study as general discussion. Note that, the discussion in Sections 5.3 and 5.4 is mainly based on the feedback from professional users, while the discussion in Sections 5.1, 5.2, and 5.5 is based on the results and feedback from novice users.

5.1 Creative Activities Induced by the Integration of Object-based Painting with Digital Painting

5.1.1 Deciding the Painting Motif. We observed that the object selection process affected the participants' choice of the motifs. We analyzed the answers to Q2 focusing on the timing of the final motif decisions and the reasons

Fig. 6. Objects prepared for the experiment

for the choice of objects, together with the video recordings of the painting process. We grouped the approaches taken by the participants in three categories T1, T2 and T3, which represent “from the beginning”, “in the middle”, and “no motif (infinite)”, respectively. This categorization was based on the timing-related words used by the participants in their responses. For example, in the response “I had no motif from the beginning. I just used objects what I thought interesting, and the result is this work,” there is no phrase related to the timing, so it was categorized into T3 (“without any motif”). (The letters in the brackets refer to specific participants.)

T1: Decide a motif beforehand and paint a picture accordingly (A, H, K, L, O).
T2: Start without a motif, but then decide one after some exploration (B, D, E, J, M, N).
T3: Try out objects that are interesting one after another without any motif (C, F, G, I).

Fig. 7 shows examples for each type of painting. In T1, the participant started with a motif and chose objects that can render the form and the color according to the chosen motif. During the process of painting, they also added other features depending on the objects they decided to use. For example, participants A and K reported that they used objects when they found interesting shapes and patterns. In T2, the participants did not clearly decide on a motif at the beginning; but the motif came up in the course of exploring with different objects on the system. For example, participant B reported wondering for a while about the motif, but then decided on a motif to take advantage of the collage created during exploration. Participant D reported that the idea of “painting an apple with (imitation of) an apple” came up from having picked up the apple casually. In T3, the artworks were created by exploring with various objects without any fixed motif. In other words, the participants used objects one after another as they wanted. They reported focusing on the colors and forms of the collage being created, and completed the artwork when they were satisfied with the overall appearances. The final images look like abstract paintings. As shown below, various objects were used in different ways through trial-and-error. We consider that the easy-to-input nature realized by direct input, real-time and co-located feedback facilitated the trial-and-error process and allowed the participants to create various styles of artworks as shown above.

5.1.2 Types of Objects Used. In total, 94 objects from 44 types of objects were utilized for painting. Here, we count non-identical objects of the same type as different objects, e.g., ace of hearts and ace of diamonds are counted as two objects. On average, 16.5 objects were utilized in one artwork (min. 6, max. 36, and SD. 8.8). According to the participants, the objects were chosen based on their mere interests, or a clear intention to capture 1) the shape (three participants), 2) the color and the pattern (six participants), or 3) both the shape, the color, and the pattern (six participants). From the personal objects that the participants brought, the following three were used for painting: the sleeve of a shirt, a candy box, and a piece of masking tape. Table 2 shows the list of popular objects used for creating artworks.

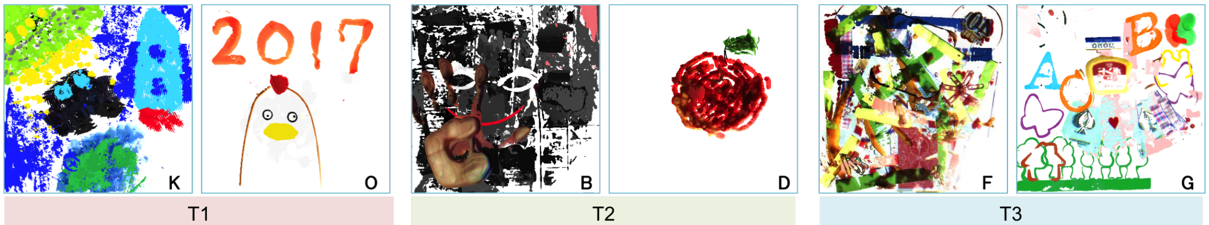


Fig. 7. Examples of artwork created by different motif decision-making processes (left: T1, center: T2, and right: T3). The letter in each picture indicates the participants ID.

The fingertip of the participant was the most used object, in which the primary purpose was to use it as an eraser, rather than capturing the color of the fingertip and painting with colors from a palette (See Fig. 8 (a)). Any object can be used as an eraser by choosing the default background color from the palette as a painting color; however, the fingertip was used most frequently. We consider that this is because a body part is most controllable in terms of the position and the contact area. Five participants used a real eraser; however, they used it to capture the logo printed on the surface of the case. A paintbrush and a pen were also commonly used objects due to their familiarity to draw lines or place dots. Other objects in the table are rather uncommon in traditional painting. Thus the participants had unique experiences with such heterogeneous and uncommon objects for painting and used them in a variety of ways as discussed in Section 5.1.3.

Table 2. Popular objects chosen in the free painting session

# of persons	Objects
11	Fingertip, paintbrush
8	Wood glue bottle, ball (orange), masking tape (cross pattern)
7	Gift wrapping bag, sponge (blue)
6	Potato chips box, imitation pear, pen (red), cup
5	Vinyl tape (green), eraser, imitation apple, sticky, masking tape (dot pattern)

5.1.3 Ways of Using Objects. The usage patterns are categorized into five groups: pressing once, pushing several times in adjacent areas (dotting), moving like scrubbing, rolling, and dropping. Table 3 summarizes the proportions of different use patterns and example objects, and Fig. 8 shows examples of input actions.

Table 3 shows that "pressing" was the dominant action in the use of object. This is because the participants tried to capture the shape and/or the pattern of the objects. Therefore, objects with a printed surface, e.g., a wood-glue bottle (Fig. 8 (b)), natural objects, e.g., leaves (Fig. 8 (c)), and objects with a unique shape, e.g., a wooden block (Fig. 8 (d)), were used in this manner. We observed that participants who used a wood-glue bottle were trying to capture the color pattern and the form with the bottom and the cap of the bottle, and the printed logo with the side of the bottle by pressing the bottom, the cap, or the side of the bottle on the IO panel, respectively. The users could press the same object in different orientations to get different forms and color patterns in the artwork. A plastic colored ball was also pressed to paint an area with different sizes as desired (Fig. 8 (e)), because the contact area changes according to the pressure on the ball.

"Rolling" of objects was facilitated by their affordances. Some participants used a plastic ball, which they rolled under their palms as shown in Fig. 8 (f). As with pressing, lines of different thickness were drawn by varying the pressure on the rolled ball. Free rolling of a ball (Fig. 8 (g)) provides an example of following its affordance. The circumference of the objects in this category is a circle. So, they are easy to roll to make a trace of the contact area on the IO panel or capture interesting patterns printed on the curved surface of the objects (Fig. 8 (h)). An interesting action in rolling is shown in Fig. 8 (i), in which the edge of a roll of vinyl tape was rotated against the IO panel to draw curved lines. A bowl was also used for the same purpose to draw a rather large arc. Due to the characteristics of the surface compliant material of the IO panel, it was not easy to draw clear lines quickly by moving thin objects; however, rolling the edge of curved objects made it easy. Cases (f) and (i) are examples of the emergent use of an object under a restriction.

"Moving" was often observed in long and thin objects, e.g., pen (Fig. 8 (j)), and soft objects (e.g., towel). As described in Section 5.1.2, it is reasonable to move long and thin objects to draw lines due to their familiarity. Soft objects such as a sponge or a towel might evoke their daily use for cleaning, i.e., wiping on the surface. So, the objects in this category were used in ways similar to their daily use.

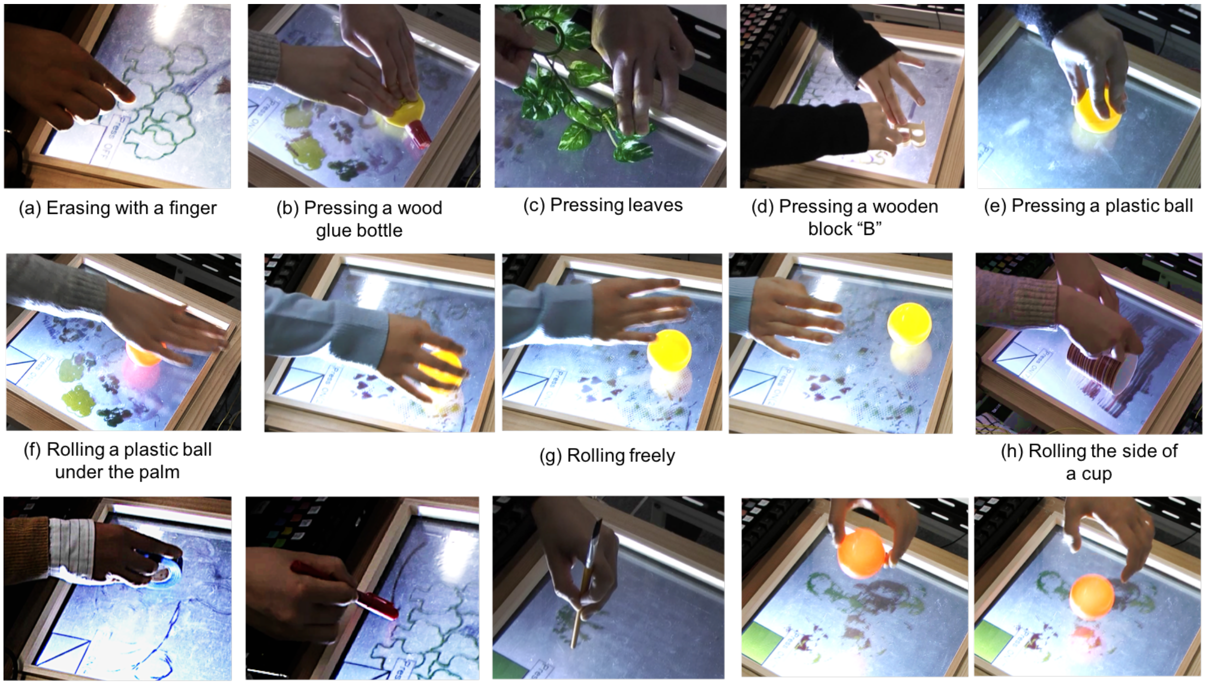
"Dotting" with objects on the IO panel was sometimes used as an alternative for drawing lines, in which objects were pushed against the panel side by side to look like a line as shown in Fig. 8 (k). Finally, "dropping" was observed only in one participant's activity, in which a ball was dropped on the IO panel (Fig. 8 (l)), and not only the contact shape and pattern of the first contact, but also the subsequent ones caused by bouncing on the panel were captured. This also reflects the bouncing affordance of a ball.

Table 3. Patterns of object use

Pattern	Ratio [%]	Example objects
Pressing	63.1	Finger, paintbrush, wood glue bottle, gift wrapping bag, post card, sticky, scissors, wooden coaster, colored paper clip, plastic ball, sponge, palm, imitation fruits
Rolling	15.4	Potato chips box (cylinder), vinyl tape, plastic ball, imitation apple, cup, bowl
Moving	13.8	Paintbrush, pen, towel, sponge
Dotting	6.2	Paintbrush, pen, finger
Dropping	1.5	Plastic ball

Thin objects with pictures were also used as shown in Fig. 9. A gift-wrapping bag was used by (a) just pressing one side of it and (b) tearing a part of it by hand. The tearable nature of this object allowed the participant to cut only a desired portion of it. Untearable flat objects such as a postcard or a plastic sleeve were (a) rubbed with a finger, (b) rubbed by another object, or (c) rolled over by another object as shown in Fig. 10. Due to the characteristic of FTIR-based contact-point sensing, a firm contact between the object and the IO panel is required. However, thin objects often roll back and are thus hard to press onto the IO panel, so the participants used other objects to get the desired pressure as in a woodcut artwork. This is evidence of the creative nature of UnicrePaint in that the users explored various input operations employing different objects to realize their desired expressions.

5.1.4 Role of Digital Edit Functionality in Painting Activity. As explained in Section 3.4, UnicrePaint allows users the benefits of a digital painting although the input is made by physical objects. When the participants were interested in a particular shape or trace of an object and desired to paint with a single color different from its original appearance, one color was chosen from the 12 colors in the system's palette. On average, the painting color was changed 26.6 times (min. 1, max. 116, and SD. 27.5). In particular, white was used as an "eraser" 4.5 times (min. 0, max. 11, and SD. 3.3). As described in Section 5.1.2, a fingertip was frequently used for erasing, and the handle tip of a paintbrush was used to erase small portions of painted area. In either case, a rough area was painted using dedicated objects, and then the eraser was applied to edit the shape. The color selection functionality enhanced the expressiveness of UnicrePaint by separating the painting color from the contact form, and provides the user with flexibility of assigning different colors from its inherent one.



(a) Erasing with a finger
(b) Pressing a wood glue bottle
(c) Pressing leaves
(d) Pressing a wooden block "B"
(e) Pressing a plastic ball
(f) Rolling a plastic ball under the palm
(g) Rolling freely
(h) Rolling the side of a cup
(i) Rolling the edge of a roll of vinyl tape
(j) Moving the cap of a pen
(k) Pushing the tip of the handle of a paintbrush
(l) Dropping

Fig. 8. Input actions with various objects.

(a) Pressing one side
(b) Tearing a part of it

Fig. 9. Input actions with a gift wrapping bag

(a) Rubbing with a finger
(b) Rubbing with a roll of vinyl tape
(c) Rolling over with a cup

Fig. 10. Input actions to capture printed patterns

In the case when participants did not like the erased area, they could undo a series of actions. The undo functionality was utilized not only for erasing, but also for canceling actions as already found in common interactive desktop applications. The actions were canceled 72.1 times on average (min. 0, max. 427, SD. 105.7), while "clear screen" functionality was used 4.2 times (min. 0, max. 14, and SD. 4.6) for resetting the entire screen. This shows that the undo functionality was effectively used to facilitate a trial-and-error process towards creating satisfactory artworks.

5.2 Enjoyment as a Product of Unique and Creative Activity through Objects

Nine participants responded "5 (enjoyed very much)", while six participants answered "4 (enjoyed)" for Q1. Also, all of them took the created artworks home. This indicates that they had positive experiences. In an analysis of their follow-up interviews, we focused on extracting the reasons for this feeling of *enjoyment* and categorized into three major factors. This categorization was done based on our intuitive judgment. However, in future research, a more objective method using automatic clustering algorithms based on semantic similarity is recommended. Each factor is analyzed in more detail below.

- Feeling of control during the painting process (B, I, M, O)
- Sense of exploration with trial-and-error (A, C, D, F, L, O)
- Freshness in painting with objects (B, E, G, H, J, K, M, N, O)

5.2.1 Feeling of Control. Four participants reported that feeling in control of their operations during the process of painting was a factor in their *enjoyment* of the system. Participants I and O told one reason for their enjoyment was that the color and the pattern of an object immediately appeared at positions where they put the object. Furthermore, the visual feedback of painting pressure was found attractive by participants M and O. Participant M reported a feeling of accomplishment when she could express darkness of the painted area by adjusting the pressure of painting. By contrast, participant O felt that her action was reflected in the system when the feedback varied from an accidental change of input pressure.

5.2.2 Sense of Exploration. In terms of the sense of exploration, participants (A, C, D, L, and O) reported that because they could not predict the result of painting with particular objects due to their first use of the system, it led them to experiment and explore the effects of using various objects. They tried to imagine these effects, and even when the actual effect was different from what they had imagined, they found the results interesting nonetheless. Participants C and D also responded that the process of seeking objects that match with the picture they wished to paint, while considering features such as shape, hardness and texture, colors and patterns was pleasant. We consider that this is a result of being able to use a diversity of objects as painting tools, which cannot be provided by the input of a single dedicated object such as a stylus and a finger. Also, the digital edit functionality allowed the participants to experiment with trial-and-error using the functions of eraser, undo, and clear screen as discussed in Section 5.1.4.

Even though in traditional drawing, users may feel more control, as they can directly manipulate the tool and its strokes, and in conventional digital drawing, users are given more freedom to undo/redo, we consider that our user feedback indicates the effectiveness of real-time and co-located presentation of successfully captured attributes of objects.

5.2.3 Freshness in Painting with Objects. Participant H noted, "I enjoyed using a rice paddle and an apple, rather than a pencil, a paintbrush, and a stylus." The other four participants also mentioned that the use of objects that are not intrinsically designed for painting made the process more enjoyable. Thus, the participants seem to perceive the freshness of being able to use physical objects to create artwork as a factor towards their enjoyable user experience. As a more concrete experience, four participants enjoyed the system due to a rare experience of transferring the patterns of objects. Among them, participants N and O reported that they enjoyed that the pattern of the object was copied precisely. Also, as discussed in Section 5.5, most participants felt like painting with objects in their response to Q3 because of the successful capture of the form and color pattern, as well as painting pressure and co-located display. We consider that such features enhance a feeling of freshness.

In addition to a sense of exploration, we consider that a feeling of freshness in painting with objects as a reason for enjoyment suggests that the uses of physical objects contributed more than just the fun of painting, while the feeling of control may be about the usability. However, we need to admit the effect of enjoyment that commonly exists in painting as Participant J stated, "I enjoyed this partially because I do not usually paint a picture." To separate such an inherent effect of painting, as previously mentioned, we compared UnicrePaint with the indirect object-based painting system I/O Brush, which is further discussed in Section 5.4.

The feeling of freshness might be lost when the activity of painting with an object becomes so familiar to the user that he/she can easily expect the results. However, given that the primary use of UnicrePaint is for recreational purposes, the frequency of use is not so high: it might be used occasionally while visiting a museum or a workshop and therefore it would impart a feeling of freshness in allowing the user to paint with newer objects every time, and to experiment with using a familiar object in novel ways; for example, painting with the handle of a paintbrush. Thus, we consider that freshness is still an effective factor for enjoyment of recreational users. Furthermore, as pointed out by the participants in the professional group in Section 5.3, some users may use the system like a paintbrush. For such users, freshness may not be so important as for recreational users.

5.3 Potential of UnicrePaint as a Recreational Tool, Art Media, and Beyond

As discussed above, novice participants used UnicrePaint in a creative manner and enjoyed the painting activity. They had no difficulty in using the system, i.e., no barrier of use. So, we can acknowledge the potential of UnicrePaint for recreational purposes such as in craft workshops, waiting rooms, museums, etc. In craft workshops, similar to pottery and glass sculpture workshops, where people create artworks using various locally available objects such as fallen autumn leaves, pebbles, shells, and so on. Artworks made with such objects might become souvenirs to recall the pleasurable events themselves.

The five art-background participants utilized UnicrePaint in a professional manner and gave concrete and insightful feedback based on their knowledge and experience. Some interesting applications were suggested in response to Q7. Participants P (an artist who often makes collages) noted that the experience was like a frottage in that a particular region of an object could be extracted and incorporated in a painting. Participants Q (a fashion designer) and R (an art researcher) suggested to utilize in action painting (gestural abstraction) by utilizing the whole body: participant Q noted “if the input space is large, I could paint using a sponge like this (opening her arms), which is good in that it enables dynamic expressions.” Regarding long-term acceptance of UnicrePaint as art media, they agreed that some users may invent their own ways to use it as a new art media like a paintbrush and paint after they became familiar with the characteristics of the system.

Participant R suggested to use UnicrePaint as a tool for reflection and ideation: “Like a block and a doll house, I can spend an unlimited amount of time before the system. I can use it as a tool to reflect on myself, or arrange my ideas while using it. It is also similar to walking while thinking.” Additionally, participant Q mentioned the possibility of making people notice materiality as a process of education: “I could notice that the surface of a leaf is not so flat as I imagined by finding the difficulty in capturing the entire surface of a leaf due to its uneven nature. This might be used for science education, in which materiality of physical objects is understood through painting activities.” These comments suggest the potential of UnicrePaint beyond making mere artwork. The system can be effectively deployed in domains such as edutainment, care of elderly people, and therapy. For instance, in edutainment, we consider that the process of finding a suitable object for painting would be effective for children to perceive and understand the surrounding environment, which seems to be implied by the art-background participants. Additionally, the trial-and-error experience would be useful for children to think actively and explore new ideas. Adult users with difficulty in holding or controlling paint brushes can create artwork with UnicrePaint because any object can be used. This suggests applications for elderly care, where UnicrePaint can stimulate cognitive functionality by creating artwork, which may be used in therapy as well.

5.4 Object-based Direct Painting as a Unique Experience

In a video-based comparison with I/O Brush [28], the art-background participants made the following comments. In response to Q8, all of them noted that in I/O Brush, the area of object surface capture is restricted by the size (diameter) of the brush, while for UnicrePaint, this area depends on what and how the object is contacted. Participant S (a photographer) noted, "the resultant picture of I/O Brush tends to be monotone. Meanwhile, in UnicrePaint, the size and the appearance of the painted result often changes unexpectedly. I like this unexpectedness." Participant Q commented, "I will need to cut an exact area of my finger later to use its captured image if I use I/O Brush on my finger. This is cumbersome and may weaken the feeling of physicality." These opinions point to a fundamental difference between indirect (I/O Brush) and direct painting (UnicrePaint), though these observations need to be confirmed by a direct comparison of the two systems.

The feeling of physicality can be enhanced by direct painting. As pointed out by participant Q in Section 5.3, a user of UnicrePaint can paint a picture using a sponge with his/her arm opening like swiping a table for cleaning, which may be quite natural in terms of both appearance and feeling. I/O Brush may also allow such styles of painting if the surfaces of a sponge are captured; however, it is not a sponge, but a brush to paint. Furthermore, participant P mentioned the uniqueness of tactile feedback in UnicrePaint, "the video of I/O Brush gave me the feeling of drawing on a screen. By contrast, UnicrePaint is a mixture of painting and working with clay because I could touch the object directly and express myself visually through it. The tactile feedback from the objects made it fun for me." We consider that this also leads to the awakening to the materiality of various physical objects.

Direct painting with co-located feedback adds a special value to the resultant artworks. Participant Q was excited to experience that the color of her finger was captured and appeared at the same position. She noted, "It would be weird to paint someone's face with the pattern of my finger, but this could be interesting because the color of a finger cannot be captured in traditional painting. I/O Brush would also allow to paint with a captured finger color, but it's different." She felt as if the pigments of her finger were exuded onto the surface of UnicrePaint, which made her feel weird to paint a human face with human pigment. Similarly, the novice participant D found it interesting to paint an apple with an imitation apple. She commented that she would not feel like using an apple if the form and color pattern of an apple needed to be registered in the system beforehand and used later. We consider that this is a unique feature of direct painting.

5.5 System Usability, Technical Limitations, and Future Improvements

5.5.1 Capturing and Feedback of the Contact Shape, Appearance, and Contact Pressure. In UnicrePaint, users do not actually paint on a physical canvas, but on a specific IO panel. This might produce a feeling of unnaturalness even though physical objects are being used. Thirteen participants responded to Q3 that they felt like painting with objects, in which eight of them rated "5 (felt strongly)" and five of them were "4 (felt)". Two participants rated "3 (neutral)". Seven participants reported that the look and feel of objects were presented realistically. Some participants also reported that the experience felt like using physical objects because of the reflection of the contact pressure to the darkness of the painted area. A participant insisted that a lack of any of the three elements, i.e., the form, the color pattern, and the contact pressure, may lose the uniqueness of UnicrePaint. However, as described below, not all the objects were used successfully. The major reason why some participants did not give a "5" rating was unexpected feedback of shape or color. Such feedback suggests that successfully capturing three pieces of information (namely, the form and the color pattern of the object contact area and the pressure applied to the panel with real-time) and co-located display add realism on the digital painting experience. This would enhance the freshness in painting and feeling of control, and thus create a pleasurable user experience.

The responses to Q4 and Q5 in the questionnaire provided us with the participants' feedback on the suitability of types of objects for UnicrePaint. The following types of objects were found to render contact shapes consistent with the user expectations: uneven objects like rice paddles, easy-to-attach material like vinyl tape, and objects with small footprints and close attachments like cookie cutters. On the other hand, the following types of objects did not yield expected appearances: objects with delicate distortions and warps like wooden coasters, objects containing air pockets like a sponge, and objects whose contact form changed due to motion like imitation flowers. The mechanism of FTIR captures only the part in contact with the IO panel, which makes it difficult to capture contact parts that do not adhere well or contain air pockets. To extend the available object for contact shape capture, an appropriate, perhaps dynamic, setting of the threshold is required to obtain a binary image.

The difficulty in painting with black objects was pointed out by three participants, which is due to the characteristic of FTIR-based contact surface detection: the IR light is absorbed into dark or black objects and permeates into transparent and lustrous objects. However, for two of these participants, it was not a critical issue. Interestingly, the third participant noted that this constraint made the painting activity more interesting. None of the participants mentioned the difficulty with transparent and lustrous objects. Given a large degree of freedom in object selection, we consider that a user will find ways to overcome these limitations.

Most participants enjoyed the pattern and the picture of the object being reflected during the painting process, confirming the effectiveness of this functionality. However, some participants, in their response to Q5, noted that subtle or dark colors were hard to capture. Subtle colors of an object reflect the projected light (the gray-level light of the color adjustment image) excessively, thereby making the captured color too bright. On the other hand, the projected gray-level light was absorbed by dark colors of an object even if the contact surface is successfully detected. Although the color adjustment image contributes in reproducing colors, it only considers the distance from the center of the light source. For improvement, the characteristics of the object's surface to be contacted with the IO panel should also be considered to absorb or enhance the reflection.

As discussed above, the fine reflection of the contact pressure made the user feel as if they were painting with the objects on a paper canvas. In the experiment, eight types of contact-pressure feedback (see Table 1) were tested, which are various combinations of four elements of color space and two ways of changing the element values. In response to Q6, ten participants preferred the feedback type where increasing pressure decreases values, i.e., the color gets darker or more somber as the object is pressed harder. The most preferred feedback type was where the luminance value in HLS color space decreases as more pressure is applied to the input panel (Type 8). Two participants (H and J) mentioned that they used more than two types of feedback based on what they wanted to render. This is an advantage of integration with digital painting: the user can switch from one expression to another at any time.

5.5.2 System Performance and Hardware Configuration. No negative comments were made by any participant regarding the processing speed and possible speed of moving objects. This indicates that the current performance is acceptable for the users. However, there were some requests for improving the form factors such as the limited size of IO panel (30 cm × 30 cm). To increase this size while maintaining the current dot pitch, a projector and a camera with a higher resolution and wider angle are needed. Another option is to utilize multiple projectors and cameras to enlarge the area virtually. In either case, the image processing needs to be tuned up to decrease the computational load, which can be realized by using the native API provided by the camera manufacturer and parallel processing libraries to exploit the GPU capabilities. Another request for improvement was the angle of the IO panel to the user. It is horizontal in the current configuration, so that the user needs to look at the panel from above to see the projected image. By tilting the far side of the panel toward the user, the visibility of the projected image can be improved. Also, some users may feel more comfortable if they can create the artwork while sitting on a chair.

5.6 General Discussion

As children, many of us felt joy in being able to paint with creased newspaper, sliced vegetables, pebbles, and so on. This tangible aspect of painting gets lost when we learn to paint with a paintbrush. The design of our system was aimed at using technology to partially restore this lost feeling, so we focused on incorporating embodiment and tangibility in our system. Moreover, when painting with various objects using our system, we implemented collocated feedback to keep the experience as realistic and natural as possible. We feel that our user study shows that these objectives are met with our prototype.

Though our system was motivated by tangible painting, which is an activity that typically children enjoy, our current prototype is aimed at novice, occasional users. This is the reason we conducted a user study with novice adult users and art professionals, which shows that UnicrePaint allows novice adult users to rediscover the joy of tangible painting, and empowers professional users with new ways of expressing themselves. At the moment, our prototype is not sturdy enough to be used by children unsupervised, but this can be an area for future research.

6 CONCLUSION

We described UnicrePaint, which was developed as a tangible tabletop interface for digital painting for novice users. The design of UnicrePaint is motivated by a hypothesis that integrating direct input from physical objects with digital painting offers unique creative experiences. To sustain engagement of novice users with the paint tool, we tried to incorporate as much physical experience of paint-like activities as possible. That is to make the users feel as if they were painting on the ground or canvas with the objects — capturing and presenting the form and the color pattern of the contact area as well as the pressure applied to the IO panel during the painting process. A technique called *selective capture* was proposed and implemented to capture input from the user while presenting the rendering of the painted work at the same time, which successfully operated the system at about 40 fps and 4 cm/s of upper limit for the painting speed. The middle level bright color was highly reproducible, while subtle and dark colors became, respectively, darker and brighter than the true colors. Additionally, a set of digital edit functionalities were introduced to avoid disengaging the user with a creative tool due to a fear of failure and facilitate creative painting through trial-and-error processes.

A user study with 15 novice users showed that UnicrePaint facilitated creativity. The system supported the participants to use different objects in various manners, rather than restricting by a small number of objects such as a paintbrush and a pen. Digital edit functions such as “undo” and “eraser” supported the participants’ exploration to obtain their desired expression through trial-and-error even though there were objects that did not fully allow them to capture expected appearances. The *freedom of expression* was offered by the inherent nature of UnicrePaint in which a number of objects can be used for expression. Moreover, it was enhanced by digitally represented information of objects that allowed the participants to use the contact form, the color patterns, and the pressure applied to IO panel separately. The participants enjoyed with UnicrePaint in terms of the freshness in painting with objects caused by successful digital replication of a paint-like activity using objects. Also, the process of exploring ways of desired expression and a feeling of control during the painting process contributed to their enjoyable experiences with the system. UnicrePaint was primarily designed for recreational purpose such as in craft workshops, waiting rooms, museums, etc.; the results of our user study showed that UnicrePaint offers unique experiences with painting in creative manner.

Another user study with five professional users with art-related backgrounds suggests the potential of UnicrePaint beyond mere artwork; the system can be deployed in domains such as ideation, reflection, edutainment, elderly people care, and therapy as well as using a tool for artwork such as frottage and action painting. The study with professional users also suggested that the direct input from physical objects enhances the positive feeling toward unexpectedness of expression, the materiality of various physical objects, and the feeling of physicality, after a video-based comparison with the indirect object-based painting system, I/O Brush. The feature that any object can be used for painting can make the artwork more meaningful than a mere image. The objects used in creating the artwork create another dimension of meaningfulness, which can stimulate user creativity in new ways.

ACKNOWLEDGMENTS

This research was partially supported by the HAYAO NAKAYAMA Foundation for Science & Technology and Culture (No. 27-B-42). We would like to thank the participants in our user study experiment for their cooperation. We are also grateful to Ms. Patricia McGahan for commenting on an earlier draft of the paper.

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Received February 2018; revised August 2018; accepted October 2018