# ThermalPen: Investigating the Influence of Thermal Haptic Feedback for Creativity in 3D Sketching

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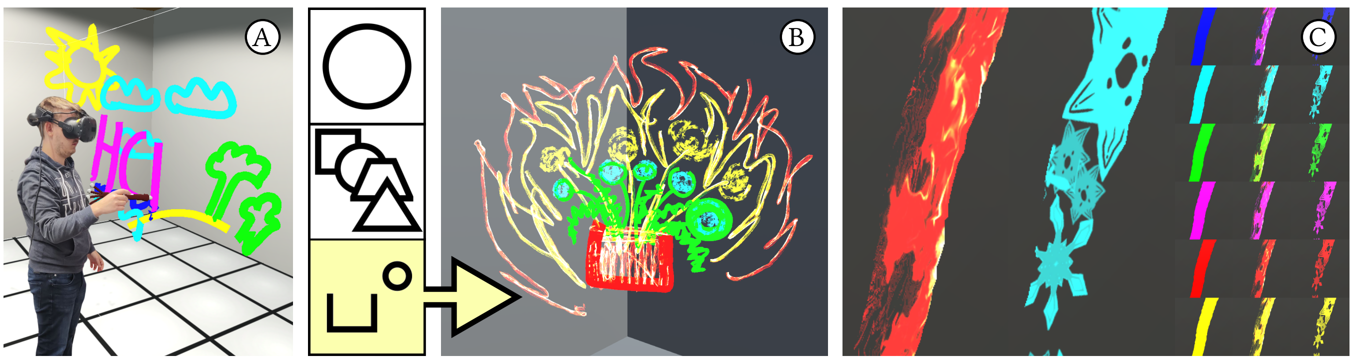


**Figure 1: A) A user utilizing ThermalPen to sketch in Virtual Reality, B) Sketch drawn during the user study. Participants were presented with the conditions on the left side and had 5 minutes to produce a sketch. Drawing experts then scored each sketch; the example got a high creativity score. C) ThermalPen has 18 color-texture combinations. The red flame texture and the cyan snow texture are displayed separately for better comparison.**

## ABSTRACT

This paper presents ThermalPen, a novel device for 3D sketching that utilizes thermal feedback to allow users to feel the materiality of their sketches. The pen lets users draw using six colors and three textures mapped to different temperatures. Our goal is to investigate the influence of thermal feedback on user creativity for 3D sketching. In a user study with 24 participants, we asked them to draw with and without thermal feedback. Our results show that thermal feedback improved user creativity for specific tasks. Qualitative results also indicate an effect on the user experience. Our work contributes to understanding how thermal feedback can increase user satisfaction with 3D sketching and provide insights and directions for future work.

## CCS CONCEPTS

• **Human-centered computing** → **Haptic devices**; **Virtual reality**.

## KEYWORDS

Virtual Reality, 3D Sketching, Creativity, User Experience, Haptics, Pen-input, Thermal

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## 1 INTRODUCTION

Since early history, humans have used sketching to communicate abstract, emotionally salient messages, making it a fundamental visual arts practice. As technology develops, sketching has emerged in Virtual Reality (VR), allowing individuals to work directly in 3D. This new art form called 3D sketching has the expressiveness, immediacy, and ability of traditional 2D sketching. In addition, unlike 2D sketching, 3D sketching allows for spatial awareness, presence, and multiple perspectives provided by VR [4]. 3D sketching can also enhance users' creativity, as VR enables users to expand their


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reality, freeing artists from the confines of physical space, which enhances creative thinking alongside collaboration and hedonic pleasure [30]. Thanks to these advantages, 3D sketching is becoming increasingly popular for artists, engineers, designers, scientists, and consumers for use in multiple settings [71].

In this paper, we introduce ThermalPen, a 3D sketching pen that uses thermal feedback by associating temperatures with different colors and textures. For example, when sketching a fire using red, ThermalPen allows users to feel the warmth emanating from its body, while sketching an iceberg using a blue ice texture will result in a cold temperature sensation from the pen. Our goal is to expand the users' reality, allowing them to get a new perspective on their work, which enhances the spontaneous and emotional creativity of the user [17]. Moreover, ThermalPen increases the sensory haptic feedback while 3D sketching, allowing users to embed a new meaning within their art [18]. For example, artists can change the texture of the colors to make it warmer or colder, depending on their intention. Despite the possibilities that exist to enhance user creativity by adding thermal feedback, most previous work has focused on proposing new interaction techniques and devices for 3D sketching to improve user accuracy [7, 10, 21, 79]. In opposition to them, we focus on allowing users to express themselves, explore new experiences, and have fun, which is important for 3D sketching tools that focus on art creation [8].

To gain insights into using thermal feedback while 3D sketching, we ran a user study about the effects of using ThermalPen to sketch on creativity, engagement, cognition, and user experience. We asked our participants to do three tasks in VR similar to the non-verbal tasks of the Torrance Test of Creative Thinking (TTCT) [70] with and without thermal feedback. We used those tasks as they constrain the user to specific actions, allowing us to explore how thermal feedback helps users be creative by providing a new perspective. For example, the *use* task requires participants to draw only using circles, which requires them to perceive the stimuli in novel ways [2]. Our results show that using ThermalPen while sketching improves the user's creativity for specific tasks. We also found that most of our participants preferred sketching with ThermalPen. Our contributions are:

- A new 3D sketching device called ThermalPen that uses thermal feedback to enhance the user experience while sketching.
- A user study about the influence of thermal feedback on 3D sketching creativity. Overall, we found that using ThermalPen with thermal feedback increases the user's creativity without affecting the user experience.
- Insights into using thermal feedback for 3D sketching.

## 2 RELATED WORK

Designing user interfaces for 3D sketching has been an open area of research for decades [6]. Here, we focus on pen-like devices for 3D sketching. We also discuss past work that studies the impact of 3D sketching on creativity. Finally, we discuss devices that provide thermal feedback to the user in VR.

### 2.1 User Interfaces for 3D Sketching

Previous works have proposed using pen-like devices as an interaction method for 3D sketching, as people are familiar with using a pen and do not require additional training. Examples include VRSketchPen [21], SenStylus [24], Flashpen [62], ARPen [72] and others [6, 38]. Moreover, pens allow users to utilize the precision grip, where users hold the pen with their thumb and index fingers and give precise control of the movement [23, 63]. Finally, the versatility of pen-like devices makes them valuable tools in 3D sketching systems as users can utilize them for other actions like selection [19, 72].

Regarding adding additional feedback to user interfaces to increase the user experience, most devices use force feedback to allow users to touch virtual objects like surfaces [24, 45, 52] or virtual canvases [21, 27, 49], as force feedback gives users more control over their stroke [46, 47, 68]. For example, Mohanty et al. [49] uses a force feedback pen to snap the tip to a virtual canvas. Another example is VRSketchPen [21], which uses vibrotactile feedback to emulate drawing on different surface types. Finally, Drawing on Air [46] and Dynamic Dragging [47] use haptic feedback to help users create smooth transitions between curves. However, most of these works focus on improving the user accuracy while drawing. Thus, we extend prior work by evaluating ThermalPen [38], a device for 3D sketching that utilizes thermal feedback to enhance the sketching experience of the user, not their accuracy.

### 2.2 Creativity Research

3D sketching is a medium that can improve user creativity, especially in the early conceptual stage of design where ideation is important [42]. Past work has found that 3D sketching affects the act of ideation [16, 20, 25, 39, 44, 55, 76]. For example, Yang et al. [76] compare 3D sketching with paper-and-pencil. Another proposal focuses on a specific task, like designing shoes [20]. Other user studies focus on analyzing the design outcomes of a task. For example, Seybold and Mantwill [65] evaluate how 3D immersive sketches affect product data management systems. Outside of this work on creativity, no previous work has focused on increasing the user's creativity while using 3D sketching.

Yet, the creation and evaluation of creativity support tools is a well-studied area of HCI ressearch [53, 59, 67]. Examples include work by Shneiderman [67] that discuss the different types of creativity support tools that exist, and Palani et al.'s [53] work that interviews creative practitioners to identify their behaviours. Other work has developed different tools to increase user creativity, like ambiguous stimuli [73] or tangible tools [78]. We extend this past work by evaluating ThermalPen [38], a tangible pen-like device to increase user creativity while 3D sketching.

### 2.3 Thermal interfaces

Thermal feedback can create immersive and engaging experiences [31, 43, 51, 58, 80]. For example, by increasing a sense of fear in the player [58]. Other work has used thermal feedback to provide additional user feedback [3, 50, 74]. For example, as a non-visual aid for navigation [50]. Finally, past work has used thermal feedback for remote control of robots [13, 33]. Here, we focus on systems that utilize thermal feedback to improve the user experience in

VR [12, 34, 36, 66]. Examples of these works include using thermal feedback to increase the sense of reality in fire simulations [66] and to allow users to feel materials [12].

Previous work has proposed various ways to provide thermal feedback to the user, including radiant heaters [66], flexible heat conducting tubes [34], infrared lamps and condensation chambers with directional fans [36], and Peltier devices [3, 13, 14, 31, 33, 48, 74]. Here, we focus on this technology, as it allows thermal energy to be added or subtracted. In other words, a Peltier device can create heating and cooling at once [22, 41, 77]. Examples of such devices include ThermOn [1] and ThermEarhook [51]. For VR devices, Peiris et al. [54] attached five Peltier devices directly to the VR headset to emulate a campfire experience. Balcer [5] examined the temperature perception using different color cues in VR. Their results show that blue matched cold temperatures and red matched hot temperatures, and when these combinations did not match up, participants were visibly confused. We extend this previous work by providing thermal feedback for 3D sketching.

## 2.4 Our Contribution Compared to Existing Literature

During our related work search, we found a dissociation between designing novel devices for 3D sketching and improving users' creativity while sketching. Our work aims to bridge both areas by creating a novel pen-like device that utilizes thermal feedback to allow users to feel the materiality of their sketches. Past work found that people identify the ability to see different perspectives as an aspect of 3D sketching that fosters inspiration and creativity [42]. Based on that and past work on thermal feedback's impact on the user VR experience [5] and the impact on the immersion [54], our goal is that ThermalPen will provide users novel perspectives of their work, enhancing the spontaneous and emotional creativity of the user [17]. Moreover, ThermalPen is a low complexity tangible tool [26], which makes it a device that can integrate with the current workflow of users [53].

# 3 THERMALPEN

ThermalPen (Figure 2a) aims to improve the users' creativity when 3D sketching by letting users feel a temperature change at their fingertips based on the color and texture of the drawn stroke. Our hypothesis when designing ThermalPen was to enhance the 3D sketching experience by complementing their visual experience with the possibility of feeling the materiality of their sketches using thermal feedback. We follow Hesham et al. 's [21] concept of *unconstrained haptic assistance*, as the addition of thermal feedback does affect the speed and expressiveness of sketching by constraining the user actions.

## 3.1 Pen Body

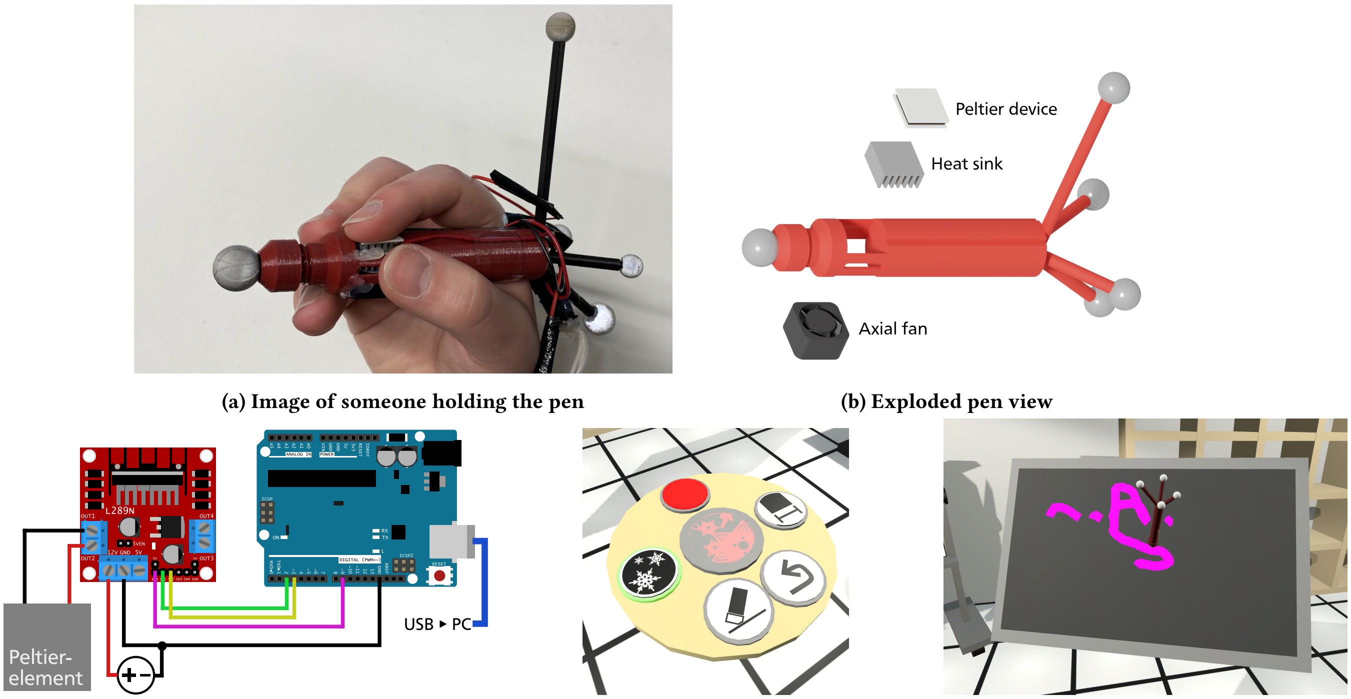
ThermalPen design has similar features as a standard pen, e.g., form, grip type, size, shape, and weight, to avoid affecting the user experience, as those factors influence the user drawing [28, 32, 56]. Having a standard pen will also encourage the adoption of the device by the final user [53]. We based this design on VRSketchPen's [21] but modified it to carry the components needed to change the pen's temperature. The main shaft is 11 cm long with a diameter of 2 cm. In the back, the pen has four legs to add the retro-reflective tracking markers, which change the pen dimensions to 17 cm x 14 cm x 7 cm. Users can screw off the pen's front cap to access a screw that mounts the front marker. The legs are separate from the pen and can also be screwed in. The back markers are press-fitted to the legs' ends. We printed the ThermalPen frame using a PLA filament with 0.2mm layer height, a 0.4mm nozzle, and 15% infill. All three printed components weighed 20 g, increasing to 44 g when adding all other elements. See Figure 2 for photos of the final devices and 3D renderings of the components.

## 3.2 Temperature Control

ThermalPen can achieve a temperature range of 16.9 °C to 57.2 °C with a maximum power draw of 1.8 W. In a pilot study with 23 participants, we asked them to sketch for 30 seconds using every possible texture-color combination available in ThermalPen to set the temperature. The participants drew a stroke for 30 s with using a specific texture-color combination. The start room temperature was 29.4°C, and participants had to raise or lower the pen temperature based on their first impression. Once they liked their choice, a researcher measured the temperature of the Peltier device using a Digital Thermometer. After this, the researcher waited for the Peltier device to return to room temperature between conditions. Participants tested 18 combinations (6 colors x 3 textures). Figure 3 shows the devices' temperatures for color, texture, and color-texture combination.

Five elements create this temperature change: a Peltier device, a heat sink, an axial fan, a microcontroller board, and a motor driver. Figure 2c shows a simplified diagram with all corresponding electrical connections. For the Peltier device, we use the *TEC1-07105*, whose dimensions are 15 mm by 15 mm when measuring the ceramic tiles and a height of only 4.2 mm. This device can produce a temperature difference of up to 68 °C with a 2.1 V maximum voltage and 4.4 A maximum current. Due to the high required current (up to 4 A), we used a *L289N motor driver* to power the Peltier device. Using this device, we controlled the direction by reversing the current flow and the speed/temperature gain by the power output. The L289N can receive up to 25 V and 2 A and is powered directly through mains by an AC to DC converter used to power home electronics (model *311P0W072*). We controlled the L289N using an *Arduino Uno* microcontroller connected to a PC via a USB. Finally, it is important to add that due to size constraints, ThermalPen does not have a temperature sensor; due to this, we calibrated the voltage and current to safe levels, where temperatures above 47 degrees are not possible.

We increased/decreased the maximum/minimum achievable temperature and the temperature change speed by keeping the side of the Peltier device facing away from the user's finger close to ambient temperature. Our goal was to shift the total temperature difference toward the intended area of the finger to achieve a more intense thermal stimulus. Like Wilson et al. [74], ThermalPen has a heat sink that shares the exact square base dimensions as the Peltier device but with a height of 5 mm. Due to the insulating air gap between ceramic tile and aluminum, we added *Arctic Cooling MX-3* thermal paste.




(a) Image of someone holding the pen

(b) Exploded pen view

(c) Electronic diagram of the temperature control

(d) Main menu of the color palette in VR.

(e) Movable sketching surface.

**Figure 2: The pen components and electronic elements that ThermalPen needs for temperature control. Additionally, the Unity3D elements in VR.**

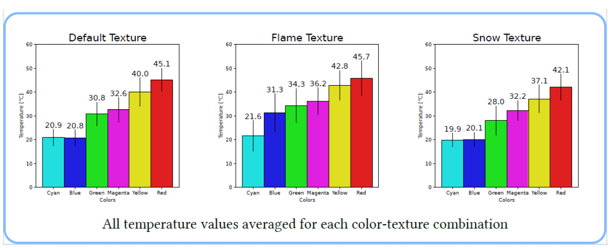



**Figure 3: All temperature available in ThermalPen.**

Finally, for better efficiency, the pen was open at the bottom, and an axial fan (*SUNON MF17080V2-1*) was installed below the heat sink to constantly blow ambient air temperature directly onto the heat sink. We attached a USB power bank to the controller to power this fan.

## 3.3 Pen Tracking

For tracking ThermalPen, we used a marker-based motion capture system (*Optitrack V100:R2*) with six cameras in a circle around the sketching area. ThermalPen includes 5 reflective markers as shown in figure 2b. One was at the front, whereas four additional ones were at the back, three behind the pen and one at a 90° angle to the pen pointing upward. The distance of the markers was different (2-8 cm). The upward leg was approximately double the length of all other markers, which created a triangle shape when observed from the side, which helped calculate the pen's orientation in 3D space. Previous work [21, 61] used similar setups for pen tracking. We removed any tracking issues with the pen by using Kalman filter [1] to smooth the pen's movement.

# 4 3D SKETCHING APPLICATION DESIGN

We used an HTC Vive as the VR HMD and developed the 3D sketching system using *Unity*. It allowed us to join the VR HMD data captured using SteamVR and the pen data captured using OptiTrack. It also enabled us access to the Arduino Uno through the serial port[2].

## 4.1 Color and Textures

Color is critical in our 3D sketching system, influencing the pen temperature. Our system allows users to sketch with six colors: the three primary colors - red, green, and blue - and the three secondary colors - cyan (green + blue), yellow (red + green), and magenta (red + blue). A color picker is in the menu in the non-dominant hand's controller.

We also provide three textures - no texture, snow, and fire. The snow texture consists of multiple differently shaped ice crystals [3]. The fire texture is a combination of shader and animation directly

[1]https://gist.github.com/davidfoster/48acce6c13e5f7f247dc5d5909dce349
[2]https://github.com/scogswell/ArduinoSerialCommand
[3]https://www.deviantart.com/mo-fox/art/Free-Firealpaca-snowflake-brushes-494514067

taken from *OpenBrush* [4], which has a non-moving seamless flame texture [5] with a smoke animation placed above which moves in the direction of the flame. The sketching direction determined the flame's orientation, and users could draw upside-down flames if their pen strokes were from left to right. We adjusted the color balance for the flame texture to offer the flame texture in all six different colors. Users can change the texture, like the color, using the menu.

## 4.2 Sketching Surface

Users utilize their index finger for thermal stimuli, plus the pen's design does not allow placing buttons near the thumb. Due to this, our system provides users with a sketching surface inside the virtual environment (Figure 2e). The sketching function is activated when the pen touches the surface, and the system automatically creates strokes following the pen's position. Additionally, the surface was colored gray to make the translucent textures more visible. Finally, users can move this plane anywhere by pressing the trigger on the controller while touching the surface with the controller.

## 4.3 Menu

We used a controller in the non-dominant hand as a menu where users could access the features mentioned above. The menu (Figure 2d) is a beige disc over the controller's touchpad, which, in the case of the HTC Vive controller, is also circular. We arranged each virtual button around this circle, which users could access by placing their thumb in their corresponding area and clicking the touchpad. This action introduced haptic feedback. In the following list, we present each option in the menu, starting from the color picker in the noon position and moving following a clockwise rotation:

- The **color picker button** allows users to select between blue, green, red, cyan, magenta, and yellow.
- The **stroke width button** allows users to change the stroke width. Our stroke size ranges from 0.5 to 5 cm; users can set it freely.
- The **undo button** allows users to undo the last stroke drawn.
- The **deleting button** allows users to delete all the drawn strokes.
- The **texture button** allows users to change the stroke's texture between fire, snow, and no texture.

# 5 USER STUDY

This user study focuses on understanding the effect of ThermalPen on 3D sketching. We aim to identify if adding a novel haptic feedback type can enhance user creativity. See Figure 4 for examples of the sketches done in the user study by our participants.

## 5.1 Research Questions

In this user study, we have the following research questions:

**RQ1:** Does using thermal feedback increase users' creativity? RQ1 is based on the ability of thermal feedback to help users visualize different perspectives when 3D sketching goes beyond the visual sense. Moreover, visualization can be used during a creative task to enhance creativity [60]. Finally, previous work has used thermal feedback to create more immersive and engaging experiences [57, 58], which might enhance creativity.

- **H1:** Thermal feedback enhances creativity while sketching in 3D.

**RQ2:** How does thermal haptic feedback affect the sketching experience? RQ2 is based on previous work that found that adding haptic feedback enhances the user experience [21]. Moreover, other work found that combining multiple means of feedback further enhances immersion [14], which ThermalPen does by combining visuals with thermal feedback.

- **H2:** Thermal feedback improves the user sketching accuracy.
- **H3:** Thermal feedback enhances user immersion and engagement.
- **H4:** Thermal feedback affects the user interface usage.

## 5.2 Methodology

*5.2.1 Participants:* We recruited 24 participants (7 female, 17 male). Age distribution ranged from 23 to 62 years (Mean = 27.8 years, SD = 9.43). Twenty participants had already used VR headsets before. Fifteen participants had prior experience in thermal feedback, 12 of which took part in the first user study. The remaining three subjects with thermal feedback participated in unrelated user studies, including thermal stimuli in VR. Finally, as we designed ThermalPen as a low complexity tangible tool [26], we tested our system with naive users to better identify the device's usability.

*5.2.2 Experiment Design:* We used two thermal feedback conditions (with and without ThermalPen) and three sketching tasks for a total of six sketches (3 x 2). Using a within-subject design, we alternate between the two sketching conditions, e.g., the first user starts by sketching with the thermal feedback enabled and then without. Then, the second participant first sketches without the thermal feedback and then with. For each condition, the order of the sketching tasks was random. Participants drew for 5 minutes for each task, for 30 minutes of drawing time. If content with their sketch, participants could finish a condition early.

*5.2.3 Tasks:* The tasks are similar to those used in the *Torrance Test of Creative Thinking* (TTCT) [70] to measure creativity. We choose those tasks as they provide us with non-verbal tasks that measure the creativity aspect we are evaluating, e.g., the ability to gain novel perspectives. They also allowed us to evaluate the participants' ability to embed meaning into the sketch, as they used geometrical shapes without meaning as a base. Yet, we did not follow the TTCT evaluation, which consists of verbal and non-verbal parts and has strict guidelines. Most important, it requires people to use a pen and pencil to sketch. Instead, we ran our study in VR.

The three tasks are called use, combine, and complete. In the *use*, participants can only sketch circles of arbitrary size. Based on the TTCT explanation, this task tests the ability of a person to find a purpose for something that has no definite purpose and to elaborate it so that a clear purpose emerges. It evaluates originality, elaboration

[4]https://openbrush.app/
[5]http://www.textures4photoshop.com/tex/fire-and-smoke/fire-flame-border-free-seamless-texture.aspx

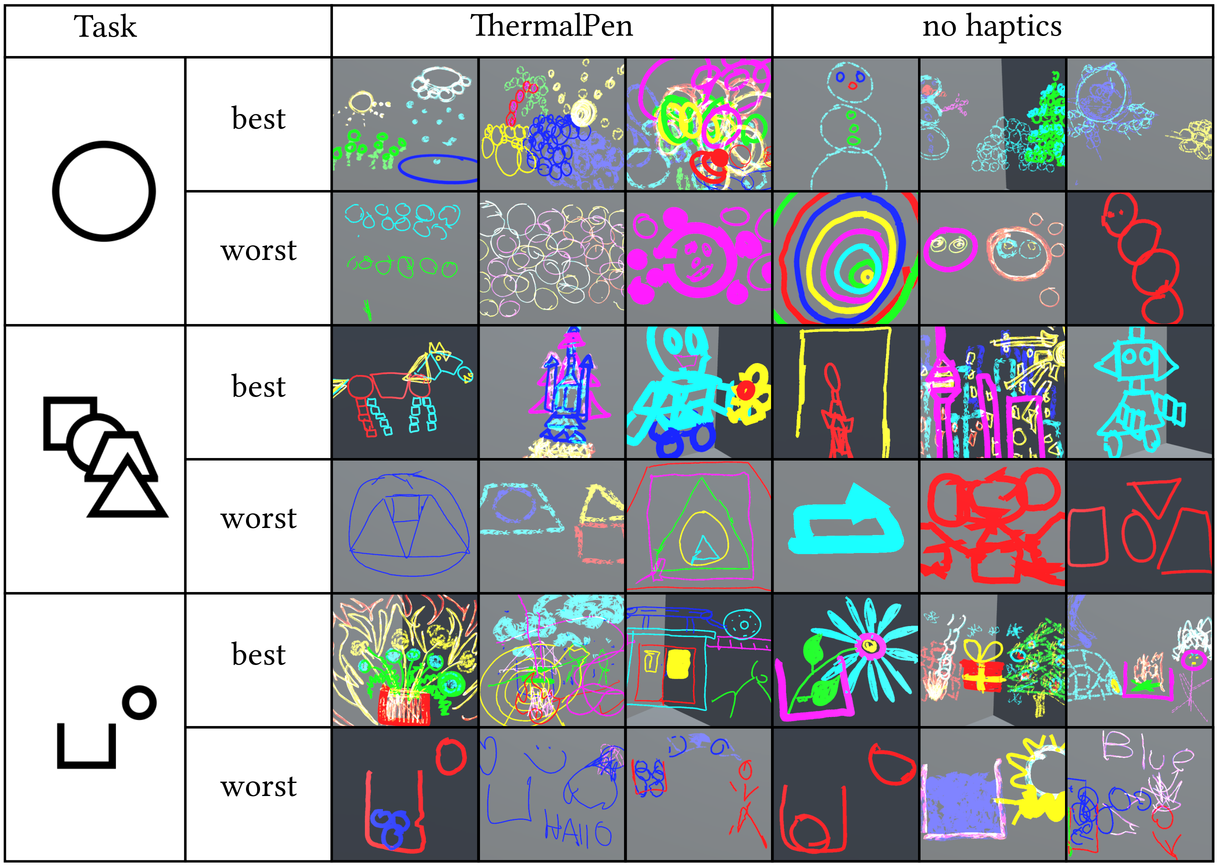



**Figure 4: Examples of participant sketches done during the user study, filtered by best and worst creativity scores.**

and creative strength. In the *combine* task, participants could draw using squares, trapezoids, and triangles of any size and in any orientation they wanted. This task requires repeatedly returning to the same stimulus, perceiving it differently, and disrupting structure to create something new. It measures fluency, originality, elaboration and creative strengths. Finally, in the *complete* tasks, participants must retrace two initial shapes (circle and square without one side) with the same proportions, position, and orientation as the example. After that, they can draw any shape they want. This task calls into play the need to structure, integrate and present an object, scene or situation. It measures fluency, originality, elaboration, resistance to premature closure and creative strength.

*5.2.4 Apparatus:* We experimented on an i7-4790 quad-core 3.6 GHz, 16 GB RAM desktop PC with an NVIDIA GeForce GTX 970 graphics card fitted onto a Gigabyte B85M-D3H motherboard. We used an HTC VIVE headset and an Optitrack V100:R2 motion capture system with six cameras (sub-millimetre accuracy) to track the pen at 100 Hz. The virtual environment was running on the same desktop computer as the application needed to update the pen's position. We provided participants with a 2.5m x 2.5m sketching area free of obstacles with full 360 degrees of rotational freedom. Users sketch on a canvas inside the virtual environment and utilize a color palette to change the stroke's properties. See section 4 for a system description.

*5.2.5 Procedure:* Participants filled out a demographic questionnaire before sketching. Then, we equipped them with a VR headset, controller, and the ThermalPen. Once inside the virtual environment, we gave participants two minutes to test the sketching feature and move around to familiarize themselves with the space. Then, participants cycled over the six different sketching conditions. Figure 4 left side has the visual instructions that participants saw during each task. After participants finished drawing with one type of thermal feedback, they filled out a questionnaire about their experience. Finally, at the end of all conditions, participants filled out a final questionnaire asking about their preference regarding thermal feedback.

## 5.3 Scoring Procedure:

Three scorers with previous sketching experience who considered themselves experts evaluated all the sketches. Scorer A is in Virtual Design and has around 8-10 years of experience with virtual 3D-Design, Scorer B has over ten years of experience in craftsmanship and sketching for cosplaying and fanart, and Scorer C is studying art in school and has 4-5 years of sketching experience. The scorers did not know each other or had any interaction before or during scoring the sketches.

Independently, the three scorers gave scores for Creative Index, Creativity Score, and Shape Likeness. See subsection 5.4 for an explanation of each metric. The scoring was done inside a virtual environment using the Unity3D strokes created by the participants. First, we standardized the sketches' sizes by scaling the drawings to the same height while keeping the same proportions. We also rotated the drawings to be parallel to the camera view. By standardizing the sketches, all scorers had the same view of the sketch.

Each scorer followed a variant of the card-sort method to score the sketches. First, each scorer gave each sketch a qualitative score based on the metric evaluated. Then, the scorers compare each drawing to the other drawings by the same participant. Finally, the scorers compared each drawing to drawings with similar scores and standardized the scores across the participants. The scorer repeated this process for all evaluated metrics. Similar subjective shape-likeness scoring methods have been used by Barrera Machuca et al. [9], and others [10, 69].

## 5.4 Evaluation Metrics

Following previous work by Barrera Machuca et al. [8], we recorded and analyzed the following measures:

*5.4.1 Creative Index:* The scorers evaluated each produced sketch through the 13 sub-scores of the TTCT to calculate the creative index. These parameters are: 1) *emotional expressiveness* that measures the ability to communicate feelings through drawings; 2) *storytelling articulateness* that measures the ability to communicate an idea or story; 3) *movement or action* that measures the person's perception of movement; 4) *expressiveness of titles* that measures the ability to go beyond description; 5) *synthesis of incomplete figures* that measures the ability to mix figures; 6) *synthesis of lines* that measures the ability to mix simple shapes; 7) *unusual visualization* that measures the ability to see things in new ways; 8) *internal visualization* that measures the ability to visualize beyond exteriors; 9) *extending or breaking boundaries* that measures the ability to go beyond apparent boundaries or limits; 10) *humor* that measures the ability to depicts it; 11) *richness of imagery* that measures the ability to depicts sharp pictures; 12) *colorfulness of imagery* that measures the ability to appeal to the senses; and 13) *fantasy* that measures the ability to use fantasy imagery. The scores for each parameter were 0, 1, or 2. The sum of all 13 sub-scores determines the *Creative Index* ranging from 0 to 26, which is an objective measure of creativity

*5.4.2 Creativity Score:* The scorers gave a subjective creativity score to each sketch based on their expertise and opinion regarding creativity. This score ranges from 0-10 using integers. This parameter allowed us to identify the overall creativity displayed in each sketch.

*5.4.3 Shape Likeness:* The scorers gave each produced sketch a score ranging from 0 to 10 based on how similar the sketch shapes are compared to the sketching requirements of the task. For example, if the task requires participants to sketch a circle, scorers measure if the circle is identifiable in the final sketch. We collected this data as part of the user experience to measure the participant's ability to sketch the desired shapes.

*5.4.4 User Experience Questionnaire:* Each participant answered a questionnaire with questions about usability, creativity, and immersion. For this questionnaire, we merged questions of four questionnaires that include the Game Engagement Questionnaire [11], Player Experience Questionnaire [40], NASA Task Load Index [37] and the Creativity Support Index [15]. We merged these questionnaires due to time constraints and because multiple questions were almost identical. The questionnaire is available in the paper's supplementary material.

*5.4.5 User Preference Questionnaire:* Our participants completed a questionnaire about their preferences, e.g., do you like thermal feedback? This data allowed us to collect the participant's opinions about their experience with thermal feedback. We also asked participants to explain why they chose their preference.

*5.4.6 User Interface Usage:* We also wanted to measure the user performance while sketching to understand better how thermal feedback affected their actions with the user interface. For this, we collected the following data: 1) *headset position and rotation* to measure differences in user movement while sketching; 2) *the number of strokes* sketched to measure the level of detail in a sketch; 3) *the number of button interactions* to measure the interaction with the menu; 4) *the number of color and texture changes* to measure the user's exploration of the different color-texture combinations; and 5) *sketching time* to measure how long it takes the user to sketch a stroke in a specific condition. We calculated sketching time by adding all the time the pen touched the surface during the task.

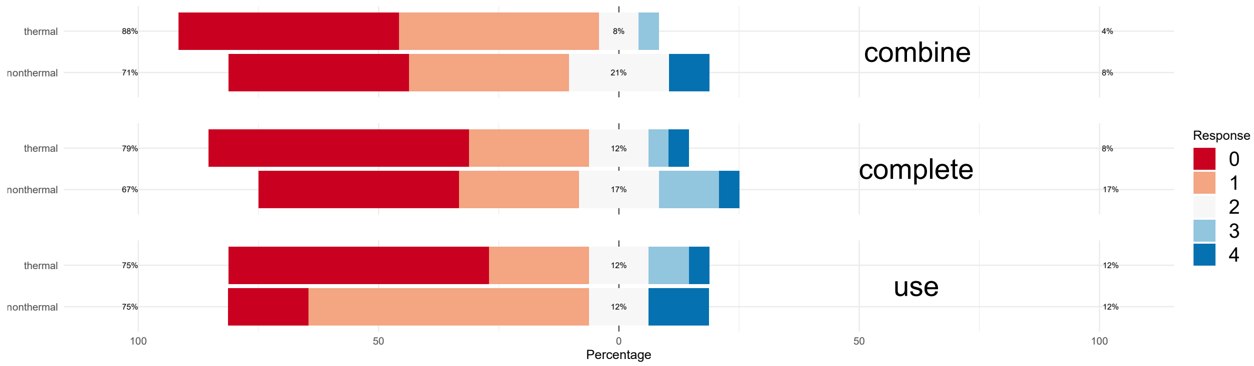
## 5.5 Results

Results were analyzed using repeated measures (RM) ANOVA in SPSS and plotted using JMP software. We used Skewness (S) and Kurtosis (K) to analyze the normality of the data, i.e., when S and K values were within ±1 [35]. All factors exhibit a normal distribution. Table 1 shows the results, and Figure 4 shows the best and worst expert-rated examples of the produced sketches by our participants for each condition and each task.

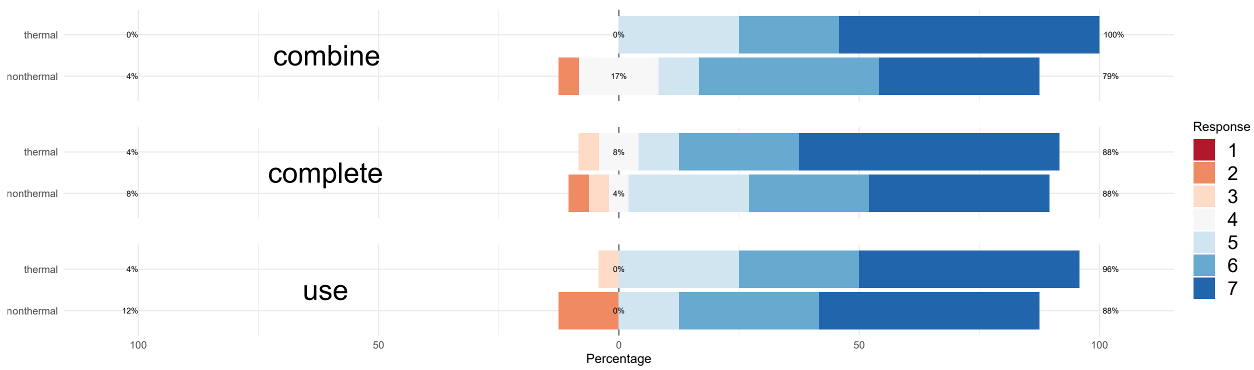
| | Thermal Feedback | TTCT Task | Thermal Feedback X TTCT Task |
|---|---|---|---|
| Creativity Index | $F(1, 23) = 0.26$, $p = 0.61$, $\eta^2 = 2.33$ | $F(2, 46) = 2.78$, $p = 0.72$, $\eta^2 = 23.62$ | **$F(2, 46) = 17.79$, $p = <0.001$, $\eta^2 = 50.97$** |
| Creativity Score | $F(1,23) = 0.48$, $p = 0.48$, $\eta^2 = 0.96$ | $F(2,46) = 1.04$, $p = 0.35$, $\eta^2 = 2.45$ | **$F(2,46) = 12.07$, $p = <0.001$, $\eta^2 = 29.41$** |
| Shape Likeness Score | $F(1,23) = 3.46$, $p = 0.75$, $\eta^2 = 4.45$ | $F(2,46) = 2.15$, $p = 0.13$, $\eta^2 = 5.01$ | $F(2,46) = 1.45$, $p = 0.24$ $\eta^2 = 3.17$ |

**Table 1: RM ANOVA results for the measures of the user study 1.**
**The statistically significantly different factors are shown in bold.**

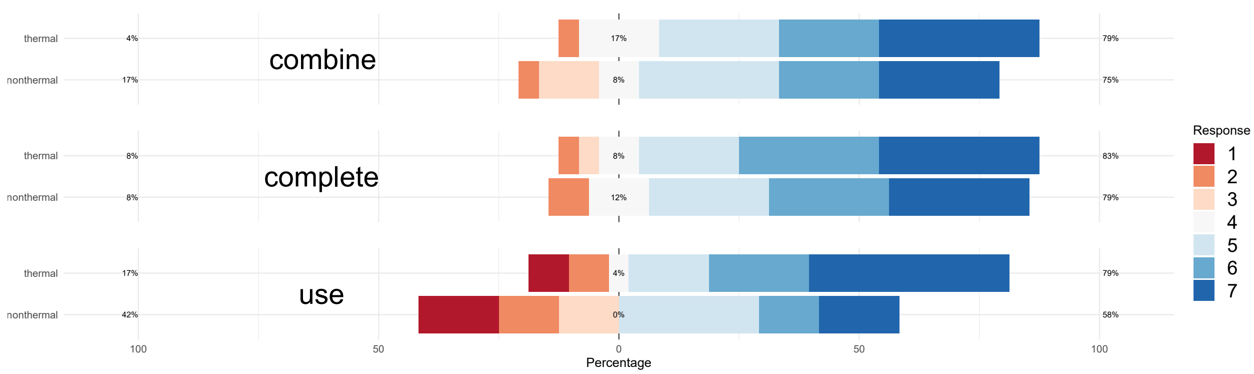
*5.5.1 Creativity:* We tested two ways to measure creativity: the *creativity index* and the *creativity score*. We did not find a significant difference in feedback for the creativity index (thermal: 10.67, SD=3.99; nonthermal: 9.09, SD=4.28) or creativity score (thermal:




(a) Questionnaire Item 2: I found using it tiresome.




(b) Questionnaire Item 12: Using the device to sketch was entertaining.




(c) Questionnaire Item 25: I was able to produce what was worth the effort required to produce it.

**Figure 5: For the three significant results of the user study questionnaire, the top bar represents thermal feedback for each graph, while the bottom bar shows the results without feedback.**

5.82, SD=1.84; nonthermal: 5.02, SD=2.27). There was also no significant difference in task type for the creativity index (use: 8.39, SD=3.69; combine: 9.6, SD=4.15; complete: 11.64, SD=4.17) or creativity score (use: 4.9, SD=1.91; combine: 5.27, SD=2.12; complete: 6.09, SD=2.1). Yet, we found an interaction on Thermal Feedback X Task (See Table 1) for creativity index and score.

*5.5.2 Shape Likeness:* Figure 6a shows the mean creativity score, and Figure 6b shows the mean creative index by task. There was no significant main effect of thermal feedback on *shape likeness* scores (thermal: 5.5, SD=1.74; nonthermal: 5.37, SD=1.9), nor on task (use: 5.8, SD=1.96; combine: 5.5, SD=1.7; complete: 4.9, SD=1.64) or an interaction thermal feedback x task (use + thermal: 5.6, SD=1.74;

use + nonthermal: 5.9, SD=2.21) (combine + thermal: 5.6, SD=1.87; combine + nonthermal:5.36, SD=1.72) (complete + thermal: 5.2, SD=1.64; complete + nonthermal: 4.77, SD=1.65).

*5.5.3 User Experience + Preference:* The qualitative results indicate that users subjectively felt a difference in the user experience. For example seven participants mentioned that *[they] had more fun using ThermalPen instead of a normal pen* (p9, p14, p15, p16, p17, p20 and p21). Eight participants also considered using ThermalPen a *more interesting way of sketching* (p2, p3, p5, p7, p8, p10, p17 and p23). When talking in specific about their experience with thermal feedback, seven participants wrote that thermal feedback *boosted their creativity* and created *a more enjoyable experience* (p2, p3, p7, p8, p10, p14, and p17), and two participants also said that *the temperature was comfortable and suited their preferences* (p5 and p12). Yet, we did have some participants complain about their experience. For example, four participants mentioned that *the temperature was uncomfortable and rather annoying* (p6, p16, p23, and p24), and one participant said that *[it] hurt they finger a little bit by drawing too much red fire* (p13). However, one participant was in favour of too intense thermal stimuli since *it made sense as [they were] drawing flames* (p18).

*5.5.4 User Interface Usage:* We found that the task affected the participant's user interface usage. For sketching time, we found that the task affected the participant's sketching time, but there was no effect based on thermal feedback. For example, the use and combine tasks increased the total sketch time (use - 90.21, SD = 50.86; combine - 101.5, SD = 42.83).

During the *use* and *combine* tasks, participants changed the texture nearly twice as much on average with thermal feedback (use + thermal: 4.08, SD=3.75; use + nonthermal: 2.67, SD=2.99) (combine + thermal: 4.17, SD=4.62; combine + nonthermal: 2.42, SD=2.71). The *complete* task had no difference between thermal feedback and no feedback, although the standard deviation was high (complete + thermal: 4.29, SD=5.56; complete + nonthermal: 4.25, SD=6.26).

This is reflected by the number of pen strokes, which also saw an increase for the *use* and *combine* tasks (use + thermal: 59.38, SD=34.97; use + nonthermal: 55.25, SD=27.59) (combine + thermal: 44.75, SD=21.39; combine + nonthermal: 40.51, SD=21.04). The *complete* task had an increase in pen strokes (complete + thermal: 50.79, SD=19.16; complete + nonthermal: 56.04, SD=26.90).

For the number of color changes, only the *combine* task had an increase in average color changes (combine + thermal: 8.79, SD=4.19; combine + nonthermal: 7.5, SD=6.27). The *use* and *complete* tasks showed little differences in color changes (use + thermal: 8.79, SD=6.40; use + nonthermal: 9.04, SD=7.07) (complete + thermal: 10.42, SD=6.05; complete + nonthermal: 10.38, SD=7.82). Although, we can observe that colors were changed more frequently for the *complete* task.

## 5.6 Discussion

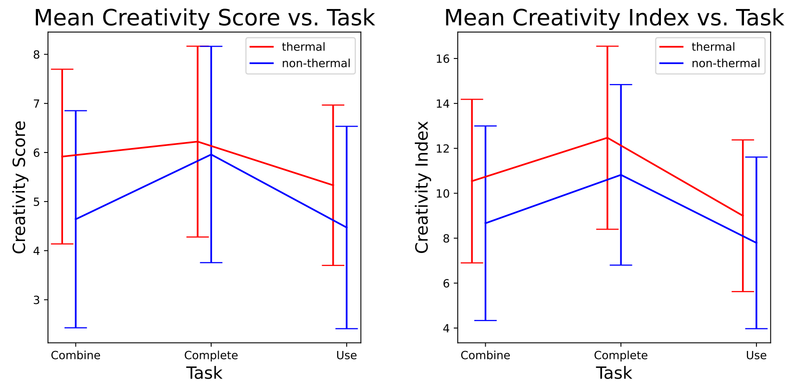
Our first hypothesis *H1* was that thermal feedback enhances creativity while sketching in 3D. For our experiment, we got two scores for creativity: the Creative Index from the TTCT scoring method and a Creativity Score given by our scorers based on their expertise. Our results show that the rating of the scores was not significantly different when using thermal feedback than without it. We also found that the type of tasks did not affect the user creativity, as more restrictive tasks (use and combine) had similar scores than less restrictive ones (complete), which is interesting because restraining a task can often help with creative solutions [64]. Yet, there was an interaction between thermal feedback and task, showing us that thermal feedback improves creativity for some tasks. When analyzing the data, we can identify that thermal feedback improved creativity over no feedback for the combined task, as shown by the creativity score and creativity index results. See Figure 6a and Figure 6b for the results. Previous work found that the versatility of the medium improves creativity [75], and our results verify that thermal feedback can make 3D sketching more versatile. Based on this, we partially accept our *H1*.

Our second hypothesis *H2* was that thermal feedback improves the user sketching accuracy. For this, we analyzed the shape likeness to identify if the sketching accuracy was affected. *H3* was that thermal feedback enhances user immersion and engagement, which we measured using the Game Engagement and Player Experience Questionnaires to identify if they were affected by adding thermal feedback. *H4* was that thermal feedback affects user interface usage, and we collected various user interface usage metrics and the NASA Task Load Index questionnaire to identify if there was a difference in how the participants used the system. Finally, we collected user preferences via questionnaires to determine if a specific feature was affected by adding thermal feedback. Most of the collected data showed no statistically significant difference between conditions. Notable exceptions include the worthiness and entertainment of using thermal feedback. We also note that participants changed color more when using thermal feedback than without (See Figure 5). Moreover, our participants' qualitative data indicate a difference when sketching with thermal feedback, as shown by the survey results and their written opinions. Based on the results and the participant's comments, we accept our *H3* and *H4* but rejected *H2*.

In conclusion, our evaluation allows us to answer our research questions. For *RQ1*, we found that adding thermal feedback increases the participant's creativity while sketching in 3D, but only for specific tasks. Yet, we did identify that the addition of thermal feedback positively improves the user's 3D sketching experience, as our participants preferred sketching with ThermalPen to without and found it an interesting experience. Moreover, we identified that it even changes how users utilize the system, e.g., changing colors and textures and drawing more strokes. Finally, the lack of significance in shape likeness and sketching time tells us thermal feedback does not affect user performance or accuracy. However, user immersion engagement is positively affected by using thermal feedback. These results answer our *RQ2*.

# 6 INSIGHTS INTO THERMAL FEEDBACK FOR 3D SKETCHING

In this paper, we introduce ThermalPen, a peripheral for drawing in Virtual Reality (VR), which provides feedback using temperature (heating or cooling) while the user is sketching. We aimed to explore whether utilizing an input device that heats and cools while sketching allows users to immerse themselves in their experience and helps them be more creative by exploring more viewpoints. We




**(a) Subjective creativity score evaluated by experts averaged**

**(b) Creative index from the 13 TTCT questions averaged**

**Figure 6: Results for the user study showing the scores done by experts. The scores are averaged over all sketches and raters.**

envision the future of 3D sketching as an art form that can extend the capabilities of physical sketching in multiple ways, and for this, it is important to provide adequate tools.

ThermalPen is a proof-of-concept for 3D sketching with thermal feedback that allowed us to identify its effect on the user experience and creativity. As no previous work has explored using thermal feedback for creativity, we first identified mappings between color texture and temperature in a pilot study. Our results show that temperature-color mapping corresponds to cool-warm color theory, as cyan and blue have the coldest temperatures, and yellow and red have the warmest temperatures. These results extend previous work on temperature perception using color hues [5]. We also found that preconceived ideas of the feeling of visual textures affect the temperature of a color, as the blue flame is almost ten degrees warmer than the blue snow (31.3°C versus 20.1°C). More importantly, we identified that the temperature range was subject to each participant's comfort level. Although no participants were harmed, six complained of too intense thermal stimuli and even found it irritating. Based on this, thermal pens for 3D sketching should include an option to customize the range of thermal feedback to make the experience more comfortable for all users.

In a user study, we found that most participants felt positive and commented on the novelty of the sketching experience, that *[it] gives a broader experience [and that] without it it just feels like normal drawing* (p8). Although quantitative results failed to show a clear increase in the measure of creativity when using thermal feedback, our qualitative results were consistent. Since creativity is hard to measure, relying on qualitative results here is better. According to their qualitative answers, participants felt more creative when using thermal feedback. Moreover, it is important to consider that sketching is not always an activity that can be measured, as people sketch as a hobby or to de-stress. In these cases, adding thermal feedback might be a good option to enhance their experience and feeling of being creative. Further, with increased customization of the thermal feedback power to remove discomfort, we may see more impact on creativity as participants can focus more on the task [29]. Finally, we also identified that participants changed color more times when using thermal feedback than without. This provided evidence that the input technique changed behaviour and that our mapping between color texture and thermal feedback increased the user experience since users explored more of the available colors. Based on this, we conclude that ThermalPen fulfilled its design goal of enhancing the user experience while 3D sketching.

Our findings complement other work demonstrating that texture affects creativity when creating meaning or semiotics [18], as temperature is critical to the human sense of touch. Yet, our quantitative results reveal interaction effects between factors, indicating that further research is needed. For example, Ritter et al. [60] suggest that a longitudinal approach to measuring creativity may yield a better understanding of the factors influencing creativity. The researchers use a one-year timeline with pre-, middle, and post-measurements. Another approach to understanding the effect of thermal feedback in VR could seek to measure presence. Ragozin et al. demonstrate significant differences in presence between thermal feedback interfaces vs. control conditions for an AR game task [57]. Alternatively, thermal feedback may be more effective as a complementary sensation in immersive settings such as games, as Ragozin et al. [58] also found significant results for cold sensation in their VR game.

## 6.1 Limitations & Future Work

The user studies conducted in the context of this paper posed limitations that were needed to test our hypotheses. First, to gather specific temperature values for colors and textures, we only included six colors and three textures. Hence, many user comments focused on needing more colors and textures. Since the temperature distribution was linear, colors could be selected on the whole range of visible colors with linear interpolation between both ends. Another study could be conducted to test if including more than six colors increases creativity. Another limitation regarding the color is that ThermalPen does not have a temperature sensor, which means that when a user uses the same color/texture for long strokes, the temperature will be unreliable. Yet, our participants did not do long strokes, e.g., sketch continuously for more than 5 seconds, making the change in temperature while sketching small. Future sketching devices using thermal feedback should use a temperature sensor to prevent this issue. Second, our participants were naive users. In the future, it is important to evaluate how skill level and expertise affect the effect of thermal feedback on creativity. Third, user interaction was limited, with no means of deleting individual pen strokes or retrospective movement of drawn sketches. Our studies did not include these additional features since that might have influenced our results. Future implementations should include elements from state-of-the-art 3D sketching systems and explore other technologies like Augmented Reality and sketching on real surfaces.

Future thermal feedback devices should also include user-defined temperature ranges so that irritating or uncomfortable temperatures do not affect immersion or user experience. In addition, further customization options may involve different virtual environments, sketch surfaces in combination with vibrotactile feedback, and more sophisticated pen stroke manipulation techniques.

## 6.2 Conclusion

In this paper, we explore thermal feedback for 3D sketching. Our goal was to demonstrate the possibilities of adding innovative haptic feedback to the experience of virtual drawing in 3D space. We present ThermalPen, the first thermal pen for 3D sketching that uses temperature to enhance the 3D sketching experience of the users by warming and cooling based on the color and texture of the stroke. Within this paper, we identified the best temperature for 18 color-texture combinations. We also ran a user study to determine how ThermalPen affects the user experience and creativity while sketching. While we only identified statistically significant interaction effects between task and thermal feedback, two-thirds of the participants preferred ThermalPen over a traditional 3D sketching pen. The only negative comments were about the need for more customization of the thermal feedback, as some participants felt it needed to be stronger, and others felt conversely. Our results show the possibilities of using novel feedback types in 3D sketching and their importance in improving the user experience.

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