VRSketchPen: Unconstrained Haptic Assistance for Sketching in Virtual 3D Environments

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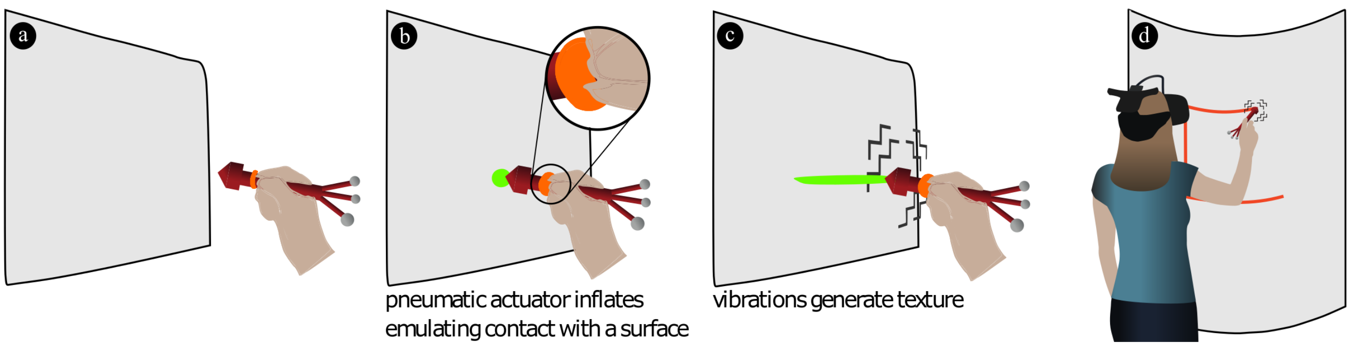

Figure 1: (a) VRSketchPen recreates the feeling of (b) contact pressure and (c) textures of surfaces, which allows users to have a more realistic experience when (d) drawing in VR. VRSketchPen also uses the unconstrained haptic feedback interaction technique, that allows users to draw in both flat and curved surfaces without snapping the stroke to a virtual canvas.

ABSTRACT

Accurate sketching in virtual 3D environments is challenging due to aspects like limited depth perception or the absence of physical support. To address this issue, we propose VRSketchPen – a pen that uses two haptic modalities to support virtual sketching without constraining user actions: (1) pneumatic force feedback to simulate the contact pressure of the pen against virtual surfaces and (2) vibrotactile feedback to mimic textures while moving the pen over virtual surfaces. To evaluate VRSketchPen, we conducted a lab experiment with 20 participants to compare (1) pneumatic, (2) vibrotactile and (3) a combination of both with (4) snapping and no assistance for flat and curved surfaces in a 3D virtual environment. Our findings show that usage of pneumatic, vibrotactile and their combination significantly improves 2D shape accuracy and leads to diminished depth errors for flat and curved surfaces. Qualitative results indicate that users find the addition of unconstraining haptic feedback to significantly improve convenience, confidence and user experience.

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CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**; *Haptic devices*; User studies.

KEYWORDS

Virtual Reality; 3D User Interfaces; Sketching; Pneumatic Actuation; Vibrotactile Actuation; Haptics

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1 INTRODUCTION

Recent advances in inexpensive, high-quality Virtual Reality (VR) headsets, such as HTC-VIVE and Oculus Rift, have promoted the interest of architects, artists, and designers to use immersive 3D sketching in their everyday activities [16, 42]. Most commercial systems, such as TiltBrush [26] and Quill [20], use 3D freehand drawing to create strokes by following the user's hand movements with a six degree of freedom (6 DOF) input device. Besides the flexibility and speed of this technique [75], users also have the advantage of being immersed inside the drawing and of sketching directly in 3D space [35]. This helps them create and visualize 3D shapes in a body-centric space. On the other hand, users need to project their shapes using perspective grids and scaffolding when drawing 3D shapes using pen and paper or a tablet.

Despite the stated advantages of immersive 3D sketching, one problem of sketching in 3D is lower accuracy compared to sketching with pen and paper [3, 77]. Some of the challenges that affect the user accuracy are the absence of physical support [3], higher cognitive [8] and sensorimotor demands [77], and the depth perception issues associated with stereo displays [6, 9, 60]. These challenges make correctly positioning a stroke in 3D space difficult. There have been different attempts to improve user accuracy while sketching in virtual environments, including the use of novel metaphors to create strokes [28, 37], beautification [5, 22], and surface snapping [2, 4, 5, 28, 42, 45]. However, these solutions constrain user actions, which can adversely influence the final sketch [48, 72].

To address the accuracy of sketching in virtual 3D environments, such as the absence of a physical surface and limited depth perception, we designed VRSketchPen – a tool for immersive 3D sketching that combines two types of haptic feedback in a new interaction technique called *unconstrained haptic assistance* (see Figure 1). The first type of feedback is pneumatic force feedback to simulate the contact pressure of the pen against virtual surfaces. The second one is a vibrotactile feedback to mimic textures while moving the pen over virtual surfaces. *Unconstrained haptic assistance* reduces the user's stroke-control errors without projecting the strokes to a virtual canvas by including the feeling of haptic textures. With VRSketchPen, we aim to enhance the user motor-control when sketching in VR, while maintaining the fluidity and expressiveness of the 3D freehand drawing interaction technique.

To evaluate VRSketchPen for sketching in a virtual 3D environment, we conducted an experiment with 20 participants where we compare pneumatic, vibrotactile and a combination of both with snapping and no assistance for flat and curved surfaces. We discovered that *unconstrained haptic assistance* made users draw more accurately in 3D than without assistance. Moreover, users could draw more accurately on curved surfaces than with snapping.

2 RELATED WORK

Designing user interfaces to fix the inaccuracies of immersive 3D sketching compared to 2D sketching [3, 28, 77] has been an open area of research for decades. In this paper, we focus on user interfaces that emulate sketching on a physical surface to prevent the problems of sketching mid-air [3] and the depth perception problems of stereo displays [6, 9, 60]. This section refers to related work on surface-snapping and physical-object interfaces, as well as interfaces for rendering force feedback and haptic textures.

2.1 Surface-Snapping Interfaces

Surface-snapping interfaces provide users with a virtual canvas where they can draw. These systems project strokes sketched by users on the virtual canvas to remove depth-related errors. Some user interfaces let users change the virtual canvas position manually [16, 28]. Others use strokes or gestures to move the drawing plane [42, 43, 52, 80]. The third set of user interfaces use predefined heuristics to automatically change the canvas position. For example, Multiplanes [5] uses the controller pose and previously drawn strokes. Finally, some interfaces use previously drawn strokes or shapes as canvases [2, 26, 28, 42, 53].

Although surface-snapping interfaces improve user accuracy, they can make the drawing less expressive [13]. They also constrain the user creativity [48, 72], as they limit the way users can create a stroke or make users re-position the drawing surface before sketching a new stroke. VRSketchPen on the other side allows users to experience unconstrained movements while maintaining expressiveness and fluidity in their interactions.

2.2 Physical-Object Interfaces

In these user interfaces, users depend on a physical surface that passively provides haptic feedback, e.g. touch devices like mobile phones and tablets [2, 11, 16, 17, 34, 45–47, 65, 80], and large screens [15, 42, 43, 59]. User interfaces on these devices translate the position of the physical surface into the virtual environment by using virtual canvases. Altering the position of the virtual canvas can be achieved by moving the device or by using 3D navigation methods to change viewpoint. Afterwards, users sketch using the touch capabilities of the device. However, when using touch devices, users can not feel the shape of the sketched object or its texture. Another limitation with mobile devices and tablets is that users need to keep the device stable with one hand while sketching, which can be tiring [32, 45]. Other user interfaces use 3D printed shapes that users can trace over [36, 74]. Nevertheless, this approach requires users to carry specific objects for each shape they want to sketch.

2.3 Force-Feedback Interfaces

Providing force sensations in user interfaces is currently accomplished using different technologies. For instance using pneumatic actuators [30, 61, 71], electrical muscle stimulation (EMS) [50, 51] and mechanical actuators [10, 29]. However, using mechanical actuators, such as exoskeletons [78], requires heavy components that lead to fatigue in a use case such as sketching.

In the context of 3D sketching, force feedback devices allow users to touch virtual objects like surfaces [23, 39, 53] or virtual canvases [24, 52]. For example, Mohanty et al. [52] use a force feedback pen to snap the tip to a virtual canvas. Force feedback devices also give users more control over their stroke [40, 41, 66]. For example, Drawing on Air [40] and Dynamic Dragging [41] use haptic feedback to help users create smooth transitions between curves. However, most of these user interfaces use a fixed force feedback device like the Touch [70] or the Phantom [69] that keeps users standing in the same place. Using VRSketchPen provides two types of haptic feedback, to feel both the shape of an object and its texture, while allowing users to walk inside the virtual environment by not fixing the system to a single position.

Many user interfaces for 3D sketching that use a force feedback device have not been evaluated. Only Mohanty et al. [52] and Keefe et al. [41] have done quantitative evaluations of the effect of haptic feedback on 3D sketching. Mohanty et al. [52] evaluated the effect of snapping on a plane using haptic feedback, and Keefe et al. [41] evaluated the effect of haptic feedback on the user stroke control. Finally, work that evaluates how haptic feedback emulates the sensation of painting with water-colors on physical objects [53] is outside the scope of this work, because we focus on 3D sketching in mid-air.

We extend prior work by evaluating the effect of different types of haptic feedback on 3D sketching.

2.4 Haptic Rendering of Textures

Moving our fingers on a surface results in vibrations that help us experience textures. Such experiences are also possible when interacting using a tool [44]. A large body of work investigates how textures of different materials can be generated [14, 62, 68]. For example, by recording vibration data of different materials, movement of a pen on a flat surface can be experienced to have different textures [14]. Co-optimization of surface and styli can be applied to closely match the haptic perception of a digital tool with the perception of a traditional one [56]. Strohmeier et al. [67] apply haptic textures to mid-air interactions with different motion to vibration mappings, such as mapping changes in rotation to vibrations. Other works relied on actuating the tip of a brush for generating textures and impact force [53], and a controller with an actuated wheel for textures [76]. However, these devices are heavy and can lead to fatigue in a use-case like 3D sketching where users do not have a physical surface to rest their hand on.

3 VRSKETCHPEN

We present VRSketchPen (Figure 2), a tool for immersive 3D sketching that uses a haptic feedback pen to help users sketch accurate shapes without constraining their actions. VRSketchPen consists of two parts: (1) a new haptic feedback pen that can emulate contact pressure and textures, and (2) a new interaction technique called *unconstrained haptic assistance*. With VRSketchPen we aim to help users sketch more accurately without sacrificing expressiveness by using haptic feedback to reduce control-errors when drawing in 3D [41, 73]. Especially those related to the lack of a physical surface [3], the high sensorimotor demands of controlling a 6-DOF device [77], and depth perception issues [6, 9, 60]. To achieve this, VRSketchPen's hardware implementation goes hand in hand with our proposed interaction technique *unconstrained haptic assistance*.

Unconstrained haptic assistance uses 3D freehand drawing combined with ungrounded haptic feedback to emulate the speed and expressiveness of sketching with pen and paper. In contrast to snapping, our interaction technique assists the users without altering their strokes. This allows users to express their ideas freely and does not limit user creativity like other CAD systems do [49]. Finally, unconstrained haptic assistance avoids breaking the design flow by removing the conscious engagement generated through constant interaction with the user interface, e.g. turning the snapping function on/off [54].

3.1 Design Considerations

The design of VRSketchPen was informed by seven parameters:

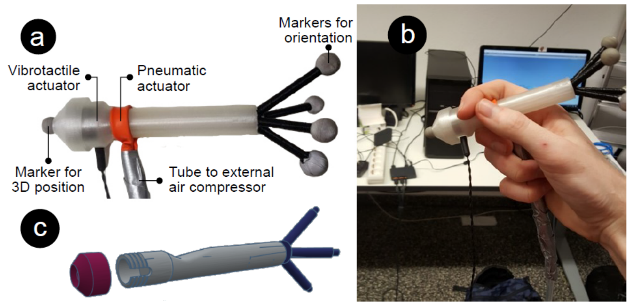

Figure 2: (a) VRSketchPen (b) used in the precision grip and (c) as a 3D model.

3.1.1 Familiarity. Most people learn how to use a pen in their infancy [21]. Furthermore, the pen remains a widely used tool in the office and by artists. Finally, for interactions in a 3D environment, pens have better performance than controllers in today's VR and AR systems [55]. Therefore, we designed VRSketchPen as a pen-like device.

3.1.2 Grip type. The design of our pen-like device encourages users to hold the pen using their fingers. Zhai et al. [81] found that using the finger muscles to grip the input device has better performance than using the wrist or elbows muscles. Users can hold the pen using the precision grip, where users grip the pen with their thumb and index finger (Figure 2b). The precision grip prevents errors when making a stroke using a pen on paper [21, 25, 64]. Moreover, the pen supports other grip types, for example, the three or four fingers grips used in Japanese calligraphy [19].

3.1.3 Size & shape. We carefully choose the size and shape of our device to help users draw more accurately, as pen design affect the user 2D drawing [27]. Design of our pen was similar to Goonetilleke et al. [27], to prevent affecting comfort and accuracy, without increasing sketching time.

3.1.4 Weight. Lightweight pens increase the user's dexterity, as the weight of a pen affects user interaction [27, 55]. For example, a lightweight pen prevents user fatigue when using the precision grip [55]. Finally, we aim for a balanced weight distribution to avoid decreasing the user performance [55].

3.1.5 Contact and Texture Feedback. Similar to real-world interactions, it is important to receive feedback on when the pen contacts a virtual surface and feeling a feedback on the pen's movements. Visual feedback is not enough to communicate these cues [44]. Similar to [68], VRSketchPen emulates textures and contact force resulting from contact with a surface.

3.1.6 Avoiding Haptic Overstimulation. Constant haptic stimulation fatigues the user [38]. To avoid this issue, our system only gives feedback when the user is attempting to sketch on the virtual surface (i.e., is close to it). If the pen is not in proximity to the system, no haptic signal is given.

3.1.7 Unconstrained Sketching. 3D environments enable the user to draw a wide variety of objects. While 2D surfaces can assist

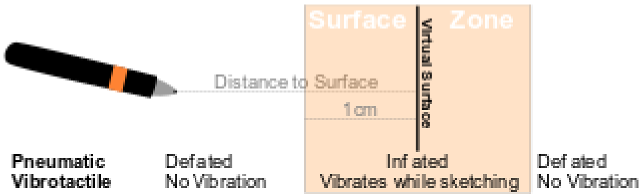

Figure 3: The *unconstrained haptic assistance* interaction technique combines vibrotactile and pneumatic feedback.

the user in sketching [5], snapping all strokes to a virtual surface limits the user's expressiveness. For example, a user might want to deviate from a predefined shape to draw an expressive fur on a 3D animal character, while staying close to the animal's body. In our work, we aim to assist the user drawing on virtual 2D surface without limiting expressiveness or constraining strokes to be on a surface.

3.2 VRSketchPen Implementation

3.2.1 Pen Design. We designed a custom pen-like device (Figure 2a). The diameter of the pen-shank is 14 mm, and the length is 105 mm. The pen also has four legs to add the retro-reflective tracking markers, whose size is 9.5 mm. The frame of the pen was printed using PLA filament and weighs 20 g. For generating vibrations, we use a single lightweight vibrotactile actuator (17 g) fitted inside a compartment at the tip of the pen. In total, the pen weighs 37 g. Figure 2(c) shows the 3D model and the printed pen. The 3D model of the pen is also available in the paper's supplementary material.

3.2.2 Vibrotactile Actuator. We use a high-fidelity vibrotactile actuator (EAI C2[1]) for rendering texture using localized high displacement vibrations (Figure 2a). The EAI C2 tactor is a linear resonant actuator that provides strong localized vibrations by using a moving contractor shielded by a passive housing. Signals to the tactor were sent using an EAI universal controller connected to a desktop computer. Vibration latency with our setup was 50 ms.

3.2.3 Pneumatic Actuator. For pressure feedback, we use a small balloon as an inflatable pneumatic actuator. It is attached at the location where the index finger contacts with the pen (Figure 2a). Our handheld prototype is connected to an external compressor and solenoid valve to keep VRSketchPen lightweight. The used air compressor (Einhell TH-AC 200/24 OF) is capable of providing up to 8 bar in pressure. Airflow from the compressor to the balloon is regulate by a solenoid valve. We used a normally closed (U.S. Solid JFSV00051) solenoid valve that is controlled using a microcontroller. Response time for the pneumatic actuator was 50 ms and inflates completely after 85 ms.

3.2.4 Tracking. To ensure accurate representation of the haptic stimulation, we tracked the pen using a marker-based motion capture system (Optitrack V100:R2). The pen is fitted with retroreflective markers for tracking.

[1]C-2 tactor from Engineering Acoustics, Inc. (www.eaiinfo.com/product/c2/, Retrieved: 25.08.2020)

3.3 Unconstrained Haptic Assistance

Our proposed interaction technique is activated depending on the distance to a virtual surface (Figure 3). The haptic assistance is activated if the distance between the tip of the pen and the virtual surface is less than 1 cm (surface-zone). We identified this value in our informal tests before running the user study. The feedback is the same, no matter if the tip is in front or behind the surface.

While activated, the pneumatic actuator indicates contact to the surface. In this state, the user feels pressure from the pneumatic actuator and texture feedback through the vibrotactile actuator, while moving the pen parallel to the surface (i.e., sketching on it). For our vibrotactile textures we use a granularity of 2 pulses per cm, 50% maximum vibration amplitude of the EAI C2 tactor and a frequency of 120 Hz. We chose these values based on prior work exploring the parameter space for generating textures [68] and our pilot tests.

To avoid fatiguing the user, once the tip of the pen leaves the surface-zone, the pneumatic actuator deflates and the vibration feedback stops.

4 EXPERIMENT

Our experiment aimed to evaluate the utility of VRSketchPen when sketching planar and non-planar strokes commonly used when designing 3D objects [63, 77]. We designed a task to evaluate VRSketchPen's utility, i.e. the combination of pneumatic force-feedback and vibrotactile textures, and how it improves user accuracy when sketching in both flat and curved surfaces.Based on prior work, we hypothesized the following outcomes:

- **H1** VRSketchPen reduces depth inaccuracies.
- **H2** VRSketchPen improves 2D sketching accuracy.
- **H3** VRSketchPen improves 3D sketching accuracy.
- **H4** VRSketchPen increases the sketching time, since participants require more time to process the haptic signals.
- **H5** VRSketchPen improves users' convenience, confidence and engagement ratings.

4.1 Methodology

In this section, we describe our experiment design, the procedure we used, our participants, apparatus, and dependent variables.

4.1.1 Participants. We recruited 20 participants (10 female) aged between 21 and 77 years (M = 30.72, SD = 13.71). Three of the participants had experience with sketching in VR, namely drawing on presentation slides in VR, from gaming and a previous research project. None of the participants had experience with snapping and haptic feedback for sketching before the experiment. Participation in our experiment was voluntary, and no compensation was offered.

4.1.2 Experiment Design. Throughout the experiment we used two surface types (flat and curved), and five levels of assistance type (vibrotactile, pneumatic, vibrotactile and pneumatic, snapping and no assistance), resulting in ten (5×2) experimental conditions. We used a balanced Latin-square to counterbalance the variables *surface type* and *assistance type* in a within subjects design. For each combination of the levels of independent variables participants sketched three shape types (triangle, rectangle and circle) performing two

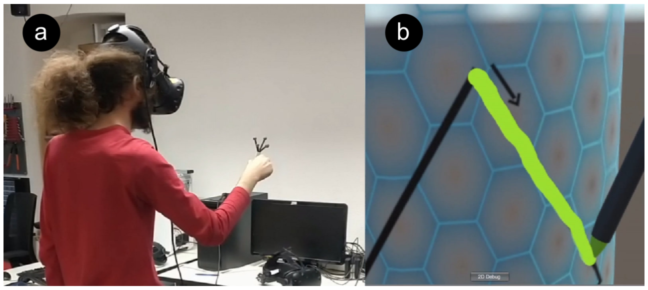

Figure 4: The setting of the experiment: (a) the physical setting, and (b) the participant view during the experiment.

repetitions for each shape. The order of the shapes was randomized. This resulted in a total of 60 strokes per participant.

4.1.3 Procedure. After obtaining informed consent from the participants, we collected their demographic data. Then, we explained the task and provided a brief overview of the procedure. The task was to trace a shape (triangle, rectangle, or circle) in a single stroke.

Every trial started with the participant standing in front of a virtual surface displaying the shape to be drawn. Our participants were instructed not to move during our study, to prevent variables like participant's movement patterns influencing the results.

There was no formal training phase. As soon as the participant felt comfortable with the environment and location of the virtual surface, they were shown the first shape. After finishing sketching a shape, the participant manually switched to the next trial. Upon completing all shapes in a condition, which is the combination of one surface type and an assistance type, our participants filled out a short questionnaire with 3 5-point Likert-scale questions. We consider this time as resting-time. Afterwards, the experiment continued with the next condition. The total duration of the experiment was approximately 45 to 60 minutes.

4.1.4 Apparatus. We conducted the experiment on a i7 dual core 3.6 GHz, 16 GB RAM desktop PC with a NVIDIA GeForce GTX 970 graphics card. We used an HTC VIVE headset [33] and an Optitrack V100:R2 motion capture system with six cameras (sub-millimeter accuracy) for tracking the pen at 100 Hz. The virtual environment was running on the same desktop computer and updated the position of the pen at 60 Hz. We provided participants with a 2.5m x 2.5m drawing area free of obstacles. VRSketchPen was used in four operating modes depending on the experiment condition:

(1) *Vibration* VRSketchPen renders vibrotactile textures to emulate movement on a virtual surface.
(2) *Pneumatic* VRSketchPen provides pneumatic force-feedback to simulate impact force with a virtual surface.
(3) *Combined* VRSketchPen renders both vibrotactile texture and force-feedback.
(4) *No* haptic feedback.

Virtual Environment: Unity version 2018.3.11f1 was used to create the virtual environment. It consisted of open space with no spatial reference except for a ground plane and the virtual surface that displays the current shape. The surface location was centered in the physical space available to our users, and its position remained

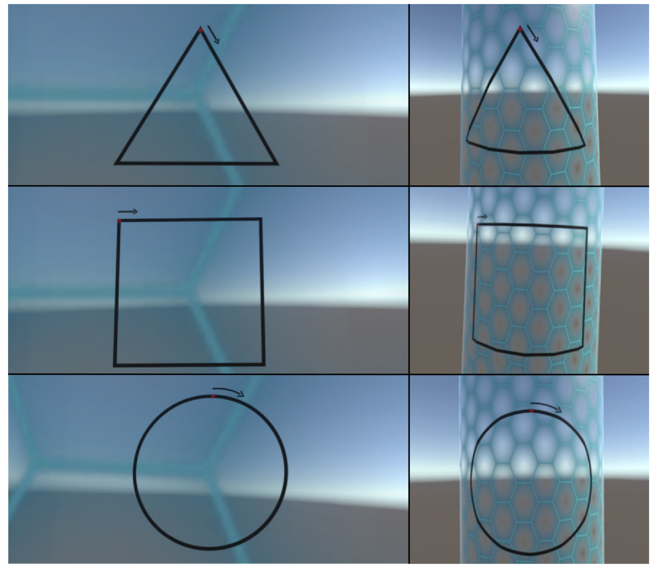

Figure 5: Participants sketched a triangle, a rectangle and a circle on flat (left) and curved (right) surfaces.

constant throughout the experiment. The surface was either curved or flat, depending on the experiment condition (Figure 5). The curved surface was a cylinder with a radius of 25 cm. The flat surface extended through the entire scene with a size of 10 m x 10 m.

4.1.5 Shapes. Participants drew three geometrical shapes that are commonly used when designing objects: a triangle, a square and a circle (Figure 5). These shapes are difficult to draw freehand without errors like waves in the strokes, non-matching corners, deviation from the drawing plane, and corrective movements [77]. For instance, even experienced designers have difficulties in precisely visualizing perspective transformations [63]. Based on their difficulty, they have been used to evaluate 3D sketching interfaces before [3, 18, 77].

The triangle base was 37 cm and its height 31 cm. The square had a side length of 37 cm. The circle had a 20 cm radius. Each shape was displayed in the middle of the surface, at a height comfortable for the participant. The position of the surface remained constant during the study.

4.1.6 Scoring. For each drawn shape the 3D coordinates of the VRSketchPen and timestamps at the running frequency of the virtual scene (60 Hz) were logged. Similar to Arora et al. [3], the data was pre-processed using a median filter with a window size of 100ms to filter out high frequency noise. The data is then approximated using piecewise linear approximation and resampled to 100 equidistant points.

To test our hypothesis, we used the following dependent variables:

- **Depth Error:** the average distance in the z-direction (perpendicular to the surface) between the participants' drawn shape and the shape displayed on the surface.

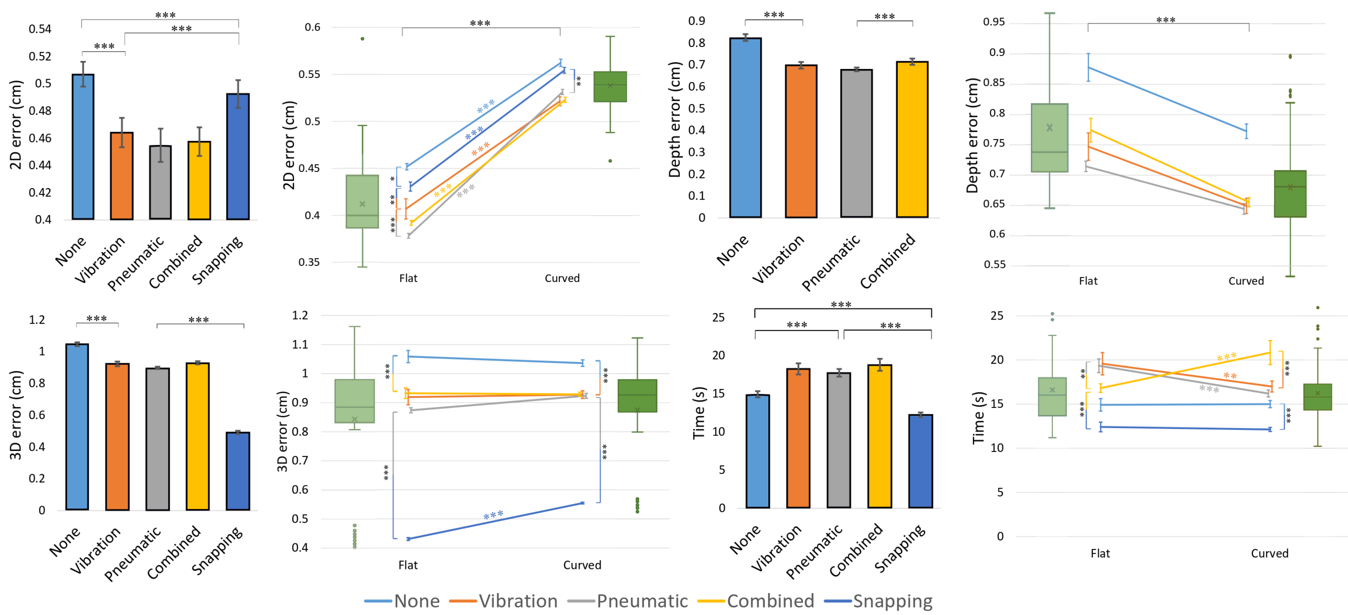

Figure 6: Average 2D, 3D, depth errors, and task completion time for each experimental condition.

- **2D Error:** the average two-dimensional error on the virtual surface between the participants' sketched shape and the shape displayed. It shows how well a user can control their arm movement without considering depth.
- **3D Error:** the average three-dimensional error between the participants' drawn shape and the shape displayed on the surface.
- **Drawing Time:** the time between the first and last point in the sketch.
- **Convenience, confidence and engagement (5-point Likert scale):** the participants' subjective estimations of their perceived convenience, confidence and engagement.

5 RESULTS

We evaluated the recorded data using a 2-way repeated measures ANOVA, followed by Bonferroni corrected pairwise t-tests where significant effects were present. We further report the eta-squared η^2 as an estimate of the effect size and use Cohen's suggestions to classify the effect size as small, medium or large [12]. For the Likert questionnaires, we performed an Aligned Rank Transformation as suggested by Wobbrock et al. [79]. We tested the data for normality with Shapiro Wilk's test and found no significant deviations. Where Mauchly's test indicated a violation of the assumption of sphericity, we used the Greenhouse Geisser method and report the ϵ.

5.1 2D Error

The analysis showed a significant ($F_{4,32.51}$ = 98.87, ϵ=.43, p < .001) main effect of the *assistance type* on the 2D error with a medium (η^2=.09) effect size. We found that pneumatic (M = 0.45 cm, SD = 0.08 cm), the combined method (M = 0.46 cm, SD = 0.07 cm), and vibration feedback (M = 0.46 cm, SD = 0.07 cm) resulted in the lowest 2D error rates, followed by snapping (M = 0.49 cm, SD = 0.07 cm) and no assistance (M = 0.51 cm, SD = 0.06 cm). Post-hoc tests confirmed significant differences between no assistance and all other conditions (p < .001), vibration and snapping (p < .001), pneumatic and snapping (p < .001) and combined and snapping (p < .001).

Second, the analysis showed a significant ($F_{1,19}$ = 841.8, p <.001) main effect for the *surface type* on the 2D error with a large (η^2=.81) effect size between flat (M = 0.41 cm, SD = 0.04 cm) and curved (M = 0.54 cm, SD = 0.02 cm) surfaces.

Finally, we found statistically significant interaction effects for *assistance type * surface type* ($F_{4,24.05}$ = 5.95, ϵ=.32, p <.05) with a small (η^2=.01) effect size. We found that pneumatic, combined, and vibration methods performed significantly better than snapping (p < .01) and no assistance (p < .001) on both flat and curved surfaces using a pairwise t-test. However, we did not observe statistically significant differences among pneumatic, combined, and vibration methods (p > .05). Figure 6 depicts the 2D error for all conditions.

Conditions using VRSketchPen showed an improvement in terms of 2D error, hence, we accept **H1**.

5.2 Depth Error

We found a statistically significant ($F_{3,40.62}$ = 108.68, ϵ=.71, p <.001) main effect of the *assistance type* on the depth error of participants with a large (η^2=.31) effect size. We found that the pneumatic feedback (M = 0.68 cm, SD = 0.05 cm) and a combined method (M = 0.71 cm, SD = 0.09 cm) resulted in the lowest depth errors, followed by vibration (M = 0.70 cm, SD = 0.10 cm) and no assistance (M = 0.83 cm, SD = 0.10 cm). Post-hoc tests confirmed significant differences between combined and none (p < .001), vibration and none (p < .001), pneumatic and none (p < .001) and combined and pneumatic (p < 0.01).

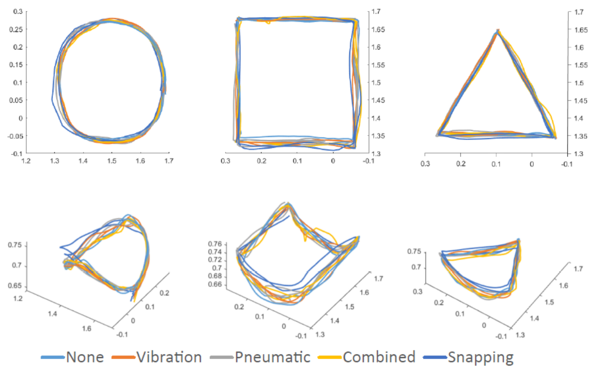

Figure 7: A circle, rectangle, and triangle sketched by one participant using five different assistance types.

Further, we found a significant ($F_{1,19}$ = 27.66, p <.001) main effect of the *surface type* on the depth error of participants with a large (η^2=.23) effect size between flat (M = 0.78 cm, SD = 0.11 cm) and curved (M = 0.68 cm, SD = 0.07 cm) surfaces.

We could not find significant ($F_{3,30.6}$ = 1.37, p >.05) interaction effects between the two factors. Figure 6 depicts the depth error for all conditions.

Compared to no assistance, VRSketchPen reduced depth errors, hence, we accept **H2**.

5.3 3D Error

We found a significant ($F_{4,35.77}$ = 955.45, ϵ=.47, p <.001) main effect of the *assistance type* on the 3D error of participants with a large (η^2=.88) effect size. We found the lowest 3D error with snapping (M = 0.49 cm, SD = 0.07 cm), followed by pneumatic (M = 0.90 cm, SD = 0.05 cm), vibration (M = 0.92 cm, SD = 0.09 cm), combined (M = 0.93 cm, SD = 0.06 cm) and none (M = 1.05 cm, SD = 0.08 cm). Post-hoc tests confirmed significant differences between no assistance and all other conditions (p < .001), as well as between snapping and the haptic conditions (p < .001).

We could not find a significant main effect for the *surface type* ($F_{1,19}$ = 4.10, p > 0.05) between flat (M = 0.84 cm, SD = 0.23 cm) and curved (M = 0.87 cm, SD = 0.17 cm) surfaces.

Further, we found significant ($F_{4,30.65}$ = 10.05, ϵ=.40, p < .001) interaction effects between *assistance type* and *surface type* with a small (η^2=.02) effect size. We found that snapping had a significantly lower 3D error in comparison to pneumatic, combined, and vibration methods, as well as no assistance for both flat and curved surfaces (p < .001). We did not observe any significant differences between pneumatic, combined, and vibration methods for both types of surfaces (p > .05), but all three of them performed significantly (p<.001) better than no assistance. Figure 6 depicts the 3D error for all conditions.

Conditions using VRSketchPen did not result in an improvement compared to snapping, hence, we cannot support **H3**.

5.4 Drawing Time

The analysis indicated a significant ($F_{4,21.23}$ = 104.62, ϵ=.28, p <.001) main effect of the *assistance type* on the drawing time of participants with a large (η^2=.31) effect size. We found that users were faster with snapping (M = 12.27 s, SD = 1.90 s), than none (M = 14.96 s, SD = 2.60 s), pneumatic (M = 17.77 s, SD = 3.21 s), vibration (M = 18.28 s, SD = 4.69 s) and combined (M = 18.82 s, SD = 5.05 s). Post-hoc tests confirmed significant differences between snapping and all other conditions (p < .001) and between none and all haptic conditions (p < .001).

The analysis could not confirm a significant ($F_{1,19}$ = 2.50, p > .05) main effect for the *surface type* between flat (M = 16.61 s, SD = 4.52 s) and curved (M = 16.23 s, SD = 4.31 s) surfaces.

Finally, we found significant interaction effects for assistance type * surface type ($F_{4,22.52}$ = 18.14, ϵ=.30, p <.001) with a medium (η^2=.08) effect size. We found that snapping had a significantly lower drawing time for both types of surfaces in comparison to other methods (p < .001). Additionally, we found that a combined method had significantly lower drawing time compared to vibration (p < .001) and pneumatic (p < .01), but on the curved surface, the combined method was significantly slower than vibration (p < .001) and pneumatic (p < .001) methods. Figure 6 depicts the drawing time for all conditions.

Compared to conditions using no haptic feedback, VRSketchPen results in an increased drawing time, hence, we accept **H4**.

5.5 Convenience

Assistance type had a significant effect on the perceived convenience ($F_{4,76}$ = 14.94, p < .001). Post-hoc tests showed that compared to no assistance, combined (p < .001), pressure (p< .001), vibration (p < .001) and snapping (p < .001) were rated more positively. In addition, snapping was rated more convenient than combined (p < .05), pressure (p < .05) and vibration (p < .01). *Surface type* ($F_{1,19}$ = 0.15, p > .05) and the interaction between factors ($F_{4,76}$ = 1.23, p > .05) was not significant.

5.6 Confidence

Participants' confidence ratings were significantly affected by assistance type ($F_{4,76}$ = 15.70, p < .001). Snapping was rated most positively compared with vibration (p < .01), pressure (p < .05), no assistance (p < .001), and combined (p < .01). Pressure (p < .001), vibration (p < .001) and combined (p < .001) resulted in significantly higher confidence ratings than no assistance. No significant effects were found for surface type ($F_{1,19}$ = 3.20, p = .09) nor for the interaction between the variables ($F_{4,76}$ = 0.86, p > .05).

5.7 Engagement

We asked our participants if they would like to use this combination of surface and assistance type when sketching in VR. The type of assistance had a significant effect on participants' ratings ($F_{4,76}$ = 14.99, p < .001). The condition with no assistance was rated by our participants as least enjoyable in contrast to pressure (p < .001), vibration (p < .001), their combination (p < .001) and snapping (p < .001).

Convenience, confidence and engagement are improved using VRSketchPen, hence, we accept **H5**.

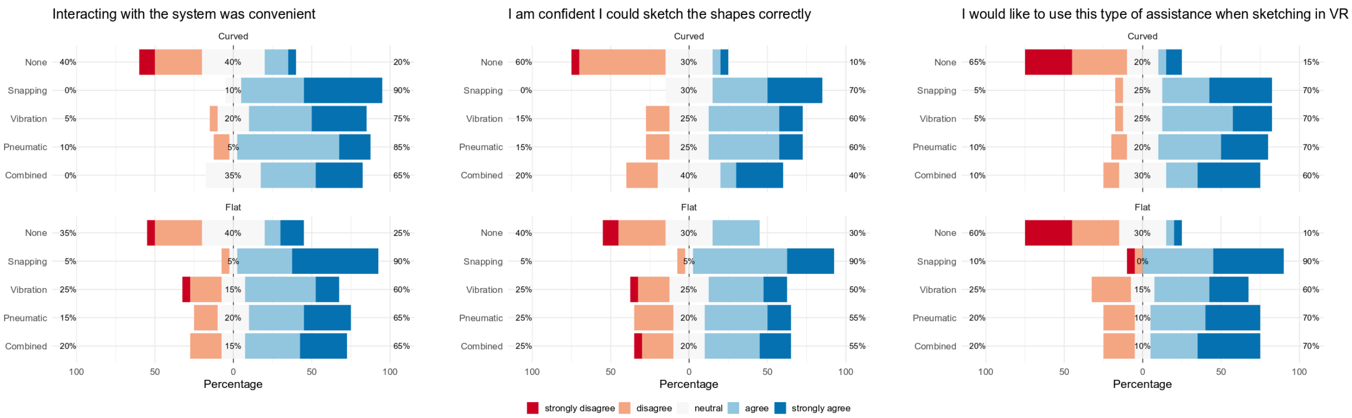

Figure 8: Participant answers to our questionnaire.

6 DISCUSSION

In this section, we discuss quantitative and qualitative results of our experiment. In general, we found that the addition of haptic feedback in VRSketchPen helped participants sketch on virtual surfaces without the need to constrain user actions. Pneumatic feedback resulted in lowest 2D and depth errors. Snapping resulted in fastest execution time and performed best for 3D error. While different types of surfaces showed comparable results for 3D error and drawing time, differences were observed for 2D and depth errors.

6.1 VRSketchPen Accuracy

In the following, measures related to accuracy are discussed.

6.1.1 2D Sketching Accuracy. VRSketchPen's haptic assistance types (pneumatic, vibrotactile and a combination) improve 2D sketching accuracy by helping users control their arm movement in two dimensions. These results indicate that haptic assistance types in VRSketchPen are valuable additions to devices for sketching on virtual surfaces.

We further noted, that the snapping technique showed a lower 2D error than no assistance, indicating that when removing depth deviation in visual output, users can focus more on controlling their arm movement.

6.1.2 Depth Sketching Accuracy. When using VRSketchPen, depth errors made by users were reduced in comparison to no assistance when drawing on flat and curved surfaces. We also identified that users made fewer errors with pneumatic assistance than with VRSketchPen's combination of pneumatic and vibration assistance (Figure 6). This indicates that for depth perception emulating contact force provides better cues than combining pneumatic with vibrotactile textures. A possible reason could be user specific preferences, e.g., P4 expressed *"I liked the balloon; the vibrations were too strong for me."*. Given that depth error with the snapping technique is always zero, we compare VRSketchPen to no assistance. These results complement previous work [3] and show that haptic feedback reduces depth perception errors when sketching on virtual surfaces.

6.1.3 3D sketching accuracy. Our results show that VRSketchPen enriches the interaction with a virtual surface and provides motion assistance in 3D space that reduces users' 3D errors compared with no assistance. However, given no depth errors for the snapping technique, 3D error with VRSketchPen was still higher than snapping, however snapping sacrifices expressiveness by contstraining user actions, which is not the case for VRSketchPen. For example, compared with no assistance, VRSketchPen reduces depth-perception errors by 18%, and motor control problems by 11.8%. This makes our proposed interaction technique useful for design applications, where expressiveness and unconstrained user strokes are valuable [1].

6.2 Drawing Time

When considering time participants took, we found that users were slower in their sketches when using VRSketchPen compared to snapping and no assistance. The combination of haptic modalities was faster on flat surfaces than curved surface. However, when using curved surfaces we observed that participants were faster using a single haptic modality than their combination. We suspect that differences in drawing time between assistance and surface types will become minimal with training [31].

6.3 Subjective Preferences

Compared to no-assistance, users' perceived ratings of convenience, comfort and confidence were significantly higher when using VRSketchPen. Although snapping was subjectively perceived as more convenient and participants felt more confident using it, they, nevertheless, expressed a high willingness to use VRSketchPen for sketching in VR. We assume that this can be explained by the two following reasons: (1) preference of the snapping technique due to visual output removing depth inaccuracies and (2) novelty effect when using VRSketchPen.

6.4 Sketching on Flat and Curved Surfaces

Sketching on flat surfaces reduces 2D error in comparison to curved surfaces. On the other hand, sketching on curved surfaces reduces depth error compared to flat surfaces. For 2D error, we assume that this difference is caused by the nature of the surface and participants' prior experience drawing in two dimension, e.g., using pen and paper. For depth, we suspect that participants concentrated more on the changing depth of the surface throughout the sketch, which resulted in lower overall depth errors.

With respect to the 3D error and drawing time, we did not observe differences between the two types of the surfaces. In comparison to previous work [3] that identified significant difference in sketching time between curved and flat surfaces. In our experiment we focused on the sketching accuracy, and so users were required to take their time while sketching which lead to slower drawing time, but therefore more precise.

7 LIMITATIONS AND FUTURE WORK

The main limitation of our user study is that participants only drew geometrical 2D shapes, even if participants drew on curved surfaces. In the future, we will evaluate VRSketchPen in complex drawing scenarios, where our participants move and draw complex 3D shapes. Yet, we expect that our results extend to complex shapes, as our results show that haptic assistance help the user's motor control and prevents depth perception errors. We only evaluated one vibrotactile texture in our study. Future works should extend this by investigating and comparing various textures for sketching, since prior work has shown that vibrotactile parameters can change the perception of virtual surfaces [68]. Another limitation with VRSketchPen is that the hardware is not self-contained, and right now restricts the movement of the user to two meters. However, future versions of VRSketchPen can use tiny position trackers based on existing VR systems [58] and a small, mobile air compressor as in Squeezeback [57], to provide mobility. Finally, beautification of pen strokes or widgets inside the VE can further assist the user in drawing more accurately.

8 CONCLUSION

In this paper, we presented VRSketchPen, a pen that combines two types of haptic feedback, extending previous work [41, 52], to produce a realistic feeling of experiencing a virtual surface. VRSketchPen enables a new interaction technique called *unconstrained haptic assistance* that helps users reduce motor and depth errors when drawing in 3D without constraining user actions. Our work extends the work by Barrera et al. [7] to include haptic feedback. VRSketchPen has better accuracy than no assistance, and in some aspects is comparable to snapping which is considered the state of the art for improving user accuracy. This makes VRSketchPen a viable option for sketching in VR. Especially when working on a new concept where an interface that does not constrain the user is needed. For example, future applications of VRSketchPen might include the use of haptic brushes in 3D sketching systems that not only change the visual aspect of a stroke, but also how they feel when the user draws with them. Involving other senses when drawing opens creative new possibilities for current 3D sketching systems.

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