Depth3DSketch: Freehand Sketching Out of Arm's Reach in Virtual Reality

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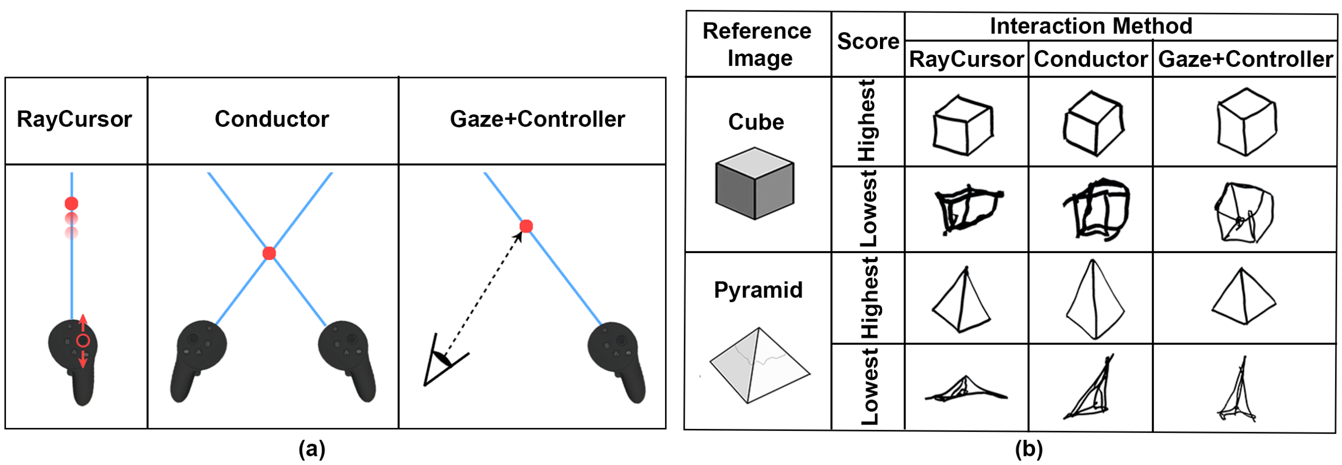

Figure 1: (a) Depth selection interaction methods used in the user study: RayCursor, where participants selected the sketching distance using the reeling method; Conductor, where the sketching distance was determined by the intersection of two rays from the controller; and Gaze+Controller, where gaze direction and a controller ray were used to select the sketching distance. (b) Example sketching results showing shape quality across interaction methods.

ABSTRACT

Due to the increasing availability and popularity of virtual reality (VR) systems, 3D sketching applications have also boomed. Most of these applications focus on peripersonal sketching, e.g., within arm's reach. Yet, sketching in larger scenes requires users to walk around the virtual environment while sketching or to change the sketch scale repeatedly. This paper presents Depth3DSketch, a 3D sketching technique that allows users to sketch objects up to 2.5 m away with a freehand sketching technique. Users can select the

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sketching depth with three interaction methods: using the joystick on a single controller, the intersection from two controllers, or the intersection from the controller ray and the user's gaze. We compared these interaction methods in a user study. Results show that users preferred the joystick to select visual depth, but there was no difference in user accuracy or sketching time between the three methods.

CCS CONCEPTS

• **Human-centered computing** → **User interface design**; **Virtual reality**; *User studies.*

KEYWORDS

3D Sketching, Eye-Gaze, VR, 3D User Interface, Multimodal

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1 INTRODUCTION

As various forms of Virtual Reality (VR) technology are increasingly available to consumers, this yielded a new medium for creative expression that is popular among artists and designers. A key design activity in many VR design applications is 3D sketching, where lines can be specified directly in a 3D body-centric space [5]. Commercial sketching systems have been gaining popularity, such as TiltBrush with over 1 million users [34], and Gravity Sketch with around 270,000 [33]. Such systems typically generate strokes that follow the user's hand movements through a six-degree of freedom (6-DoF) input device, coupled with a button click to start and end the stroke [17]. Sketching through such direct input increases flexibility, speed [42], and intuition [28]. However, as virtual environments (VEs) offer a potentially infinite space, the user should be able to sketch effectively further away as well as in near space.

When a sketch is larger than what can be reached within arm's length, commercial systems make users scale the VE, e.g., through the *grab-the-air* interaction technique [36]. Yet, past work reported that this technique reduces sketching accuracy [9]. Alternatively, users can be instructed to move to another position physically, but the user's movement is naturally limited to the physical space available. Several research efforts have explored sketching further away from the user directly without scene scaling [2, 14, 16]. Examples include SymbiosisSketch [2] that projects the stroke to a plane and the GoGo-Tapline [16] that uses an extension of the GoGo-cursor [35] to allow users to draw a line by specifying control points. While these methods permit sketching outside peripersonal space, they require users to learn new interaction techniques or to project their strokes onto shapes, which reduces the expressivity of freehand 3D sketching.

Our research aims to provide the flexibility and intuitiveness of freehand 3D sketching at a distance while sketching objects or scenes without constantly scaling the VE. We present a novel interaction technique called DEPTH3DSKETCH, where users create a stroke using the freehand sketching technique after selecting a sketching depth beyond the arm's reach, e.g., more than 70 cm away. As distant sketching is an underexplored research area, we present in this paper a user study that investigates three different interaction methods to choose the sketching depth: a) *RayCursor*, a method using the single-controller joystick, b) *Conductor*, a method using two controllers, and c) *Gaze+Controller*, a method using the eye-gaze and the single-controller (See Figure 1). Our goal is to identify which method offers the best balance of sketch quality, efficiency, and user experience in DEPTH3DSKETCH.

In summary, the contributions of this research are as follows:

- DEPTH3DSKETCH, a new interaction technique for 3D sketching that extends the sketching area up to 2.5 m.
- Identifying the most efficient interaction method to select depth for 3D sketching in terms of performance and usability.

2 RELATED WORK

2.1 3D Sketching Challenges

Current 3D sketching systems present multiple challenges, including correctly positioning a stroke in 3D space, as users are affected by the absence of physical support [3], and high sensorimotor [43] and cognitive [9, 31] demands. Moreover, VR systems also suffer from challenges like depth perception issues in stereo displays [8, 11, 12]. Multiple past works have focused on understanding the cause(s) of these inaccuracies, such as the ergonomic aspects of sketching on "air" [3, 25] and the learnability of 3D sketching [9, 43]. Finally, other work has focused on understanding the effect of the navigation method used while sketching and their impact on user performance [9]. Our work aims to reduce the need to use the *grab-the-air* interaction technique [36] to change the sketch scale.

2.2 3D Sketching Interaction Devices and Techniques

Multiple past works have addressed the issues with 3D sketching by proposing novel interaction devices and techniques for 3D sketching [5]. For interaction devices, past studies have proposed pens [17, 37, 40], physical surfaces [15, 24] and virtual surfaces [2, 6, 26]. For interaction techniques, past works have proposed the use of beautification [6, 19], novel metaphors to create strokes [23, 24, 38] or visual guides [10, 20, 39, 44] to reduce the sensorimotor and cognitive demands. Finally, a few of these interaction devices and techniques rely on multimodal interactions. Examples include bi-manual techniques [29] or using eye-gaze as an input modality [39].

One limitation of these approaches is that they mostly focus on interaction in the peripersonal space. Exceptions include systems that project the user stroke to a surface or plane far away from the user [1, 2, 14, 26] or using novel interaction techniques [14]. In contrast to these works, we present DEPTH3DSKETCH, a novel interaction technique for far-away sketching between 1 and 2.5 m from the user using the freehand sketching technique.

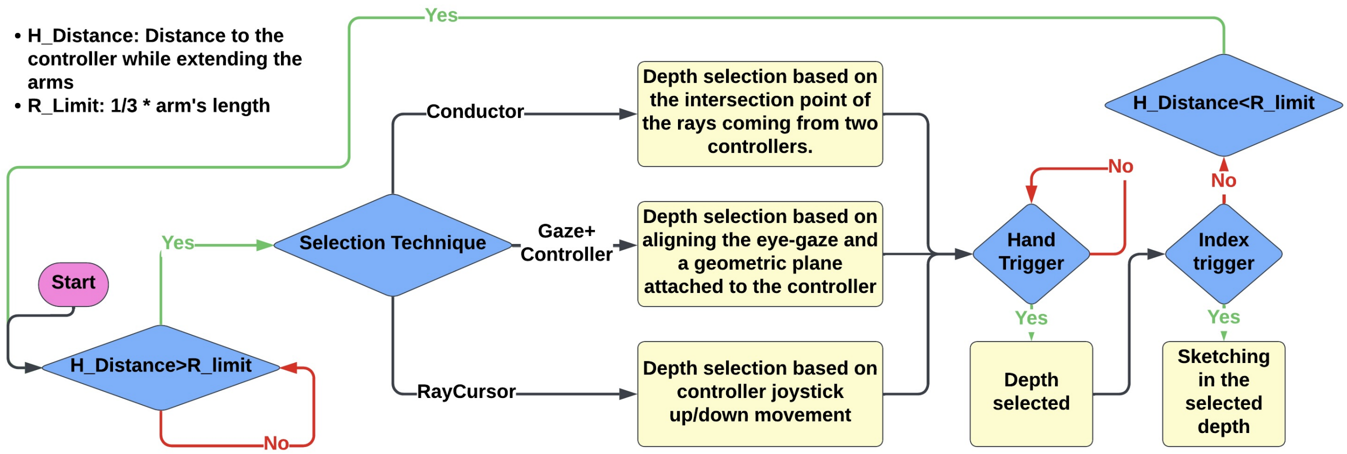

Figure 2: Depth3DSketch Technique Flow Diagram.

3 DEPTH3DSKETCH

We propose Depth3DSketch, a 3D sketching technique that allows users to sketch out of arm's reach, up to 2.5 m away from the user. Our technique involves two stages: a) the depth selection stage, where the user selects the desired sketching depth, and b) the sketching phase, where users create a stroke using the free-hand sketching technique, i.e., the stroke follows the user's arm movement. Strokes appear *directly* at the distant location in 3D space, without involving proxy strokes or near-space projection. Thus, Depth3DSketch enables freehand sketching directly at the intended distance, without requiring users to apply their spatial visualization skills, i.e., an individual's cognitive ability to mentally manipulate and visualize movements, orientations, and spatial forms of objects [13], to mentally project and align their strokes at a distance. This approach ensures that strokes are naturally integrated into the intended 3D scene, without requiring additional projection steps or external reference aids. By sketching directly at the target depth, users can thus work directly in relation to existing distant content, supporting spatial consistency and preserving the natural sketching flow. To differentiate between sketching in peripersonal space and beyond, the depth selection stage is initiated when the user's arm is extended beyond one-third of its length(Figure 2).

Depth3DSketch enables creating strokes using free-hand sketching around selected depths. It also avoids constraining the user stroke by projecting it onto a shape or requiring users to learn a new interaction technique. Yet, the most efficient method to select depth is still unclear, so we propose three different methods:

Uni-modal Method: RayCursor. As illustrated in Figure 3 (left), the uni-modal method uses the controller's joystick for depth selection, as users move a cursor along an infinite ray attached to the controller to select the desired depth for the new stroke. This method is similar to RayCursor [4], as participants hold a controller in their dominant hand that emits a ray with a cursor at its tip. Participants adjust the cursor's position along the ray to change the depth by moving the controller's joystick.

Bi-manual Method: Conductor. As shown in Figure 3 (center), the bi-manual method employs two controllers for depth selection by using the intersection of the infinite rays from each controller to select the desired depth, which is inspired by Zhang et al. [45]'s object selection technique. For Depth3DSketch, participants hold a controller in each hand, both emitting independent pointing rays. Depth selection occurs at the intersection point of these rays. While previous 3D sketching studies used bi-manual interactions to create new strokes [29], this method focuses on the selection of the spatial position of the new stroke.

Multimodal Eye-Gaze Method: Gaze+Controller. The multimodal eye-gaze method explores the use of eye-gaze for depth selection, as we utilize the combination of eye-gaze direction and controller position to specify the depth for the new stroke. Past work has applied similar techniques to other areas like 3D selection [30, 32]. For Depth3DSketch, this method uses an oblique geometric plane (invisible to the user) attached to the sketching controller. Depth selection is determined by aligning the user's gaze with this controller-anchored plane. We highlighted two depth ranges on the ground for spatial orientation: the purple region for 1–1.5 m, and the orange region for 2–2.5 m. (Figure 3 (right)). By directing their gaze, participants specify the depth at which they wish to interact, using the controller's position as a reference. Using eye-gaze to select the position on the plane follows past work on 3D sketching and eye-gaze by Turkmen et al. [39], which successfully utilizes the user's eye-gaze to position visual guides in the VE far away from the user.

4 USER STUDY

We investigated the three different depth selection methods for Depth3DSketch when sketching two basic shapes, a cube and a pyramid (See Figure 1). Our research questions are the following:

- **RQ1**: What are the differences between depth selection methods (RayCursor, Conductor, Gaze+Controller) regarding user performance (time) and accuracy (Stroke Quality and Shape Likeness) with Depth3DSketch?

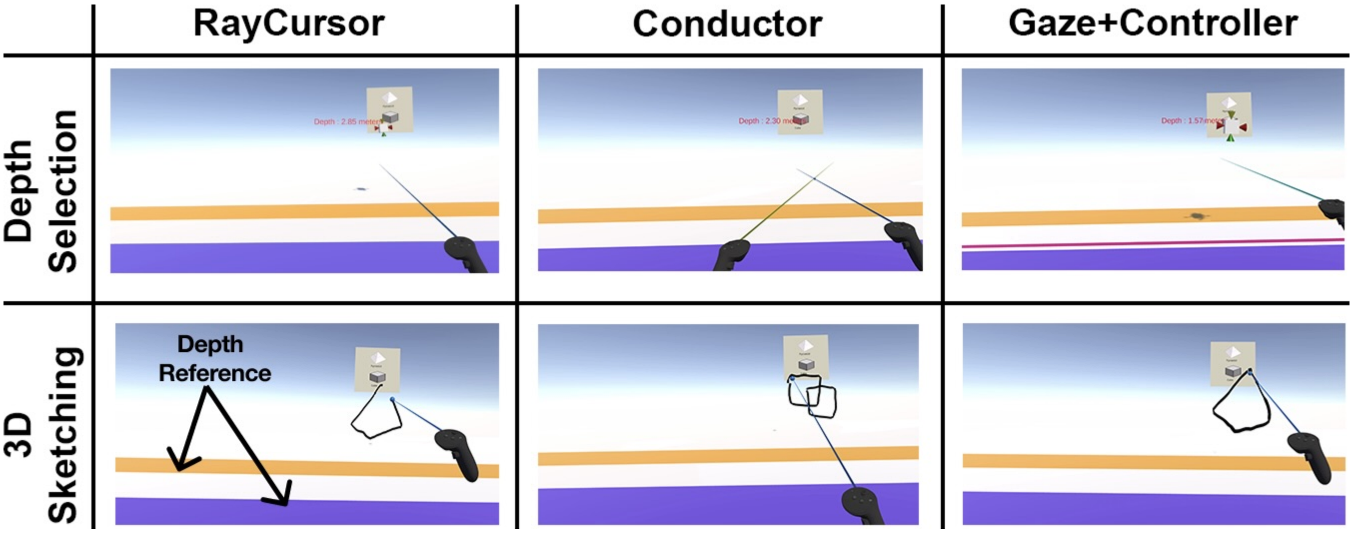

Figure 3: Sketching at-a-distance using the Depth3DSketch Technique, with illustrations of the three investigated depth selection methods. The top row shows the depth selection phase, where users select the sketching distance using different interaction techniques. The bottom row depicts the 3D sketching phase, where users draw freehand strokes at the selected depth. Reference depth positions are highlighted in purple (1–1.5 m), and orange (2–2.5 m).

- **RQ2**: How does using different depth selection methods (Gaze+Controller, Conductor, RayCursor) affect the user's ability and the perceived workload with Depth3DSketch?

RQ1 helps us understand the advantages and disadvantages of each depth selection method on the users' sketching behavior. This question centers around the physical act of creating a stroke, for which measuring motor performance and eye-hand coordination are central. **RQ2** is based on the understanding that each depth selection method has different levels of complexity. This question helps identify the effect of the method's complexity on the user's cognitive load, overall user experience, and system usability. We complement the quantitative performance evaluation by measuring the users' perceived ability to use the methods.

4.1 Methodology

4.1.1 Participants. Using G*Power software [18] with α = .05, power = .80, and a large effect size (η^2 = 0.14), we calculated the minimum sample size needed to be N = 12 for RM ANOVA. Thus, we recruited 12 participants (7 male, 5 female) from the local university, ages between 23 and 31 (M = 25.67, SD = 2.70). All participants either had normal vision or vision corrected to normal. All except two were right-handed. Seven participants reported having no experience sketching in VR, while five had participated in prior VR user studies related to 3D sketching.

4.1.2 Experimental Design. We used a three-factor within-subject design with three **Depth Selection Methods** (3_{SM} = (Gaze+Controller, Conductor, RayCursor)), two basic **Shapes** (2_{Sh} = cube and pyramid), and with two **Depths** ($2_{Sd} = 1 - 1.5m$ and $2 - 2.5m$). Each participant performed ($2_{Sh} \times 2_{Sd} \times 3_{SS}$ =) 12 sketches (12_{Dr}), leading to (12_{Dr} =) 12 Conditions (12_{Co}). The order of all conditions was counterbalanced. Each participant repeated each condition three times, resulting in ($12_{Co} \times 3_{rep}$ =) 36 trials (36_{tr}) for each participant and a total of ($36_{tr} \times 12_{part}$ =) 432 sketches.

4.1.3 Procedure. Upon arrival, participants completed a demographic questionnaire, including questions about their VR experience and sketching expertise. The experimenter then introduced the study, instructed participants to use their dominant hand, and ensured they remained seated for consistent posture and comfort throughout the session. Next, participants put on the VR headset and performed an eye-tracking calibration to ensure accurate gaze tracking. The virtual workspace height was adjusted to match each participant's eye level. The participant's arm length was measured in VR and used to set the depth selection threshold at one-third of the arm's length. To familiarize participants with the system, they completed a brief trial using the three depth selection methods. During the trial phase, they learned to extend their dominant hand beyond the one-third threshold to enter depth selection mode and press the hand trigger to confirm their chosen depth before sketching. For each method, participants selected a target depth within the predefined range by extending their arm and pressing the hand trigger once it surpassed the threshold. They sketched two 3D shapes—a cube and a pyramid—based on an isometric reference image. After completing the sketching task with a given method, participants filled out a NASA TLX questionnaire to assess their workload. This step was repeated for each of the three selection techniques. Finally, after finishing all sketching tasks, participants ranked the depth selection methods based on their preferences and provided qualitative feedback on their overall experience. Each session lasted approximately one hour, including the introduction, setup, practice trials, sketching tasks, and questionnaire responses.

4.1.4 Apparatus. For our experiment, we used a Meta Quest Pro headset with its controllers connected via Meta Quest Link to an

Intel desktop PC with an NVIDIA GeForce graphics card. The application showing the VE was developed using Unity 2022.3.21f1, featuring an open space with minimal spatial references.

4.1.5 Evaluation Metrics. We recorded and analyzed the following measures based on Barrera Machuca et al. [7]:

- *Task Completion Time:* The time from when a participant first pressed the controller index button, which initiated the sketching for a given trial, until the last time they released the button. We used this metric to compare task performance between different user interfaces.
- *Shape Accuracy*: We measured the user accuracy by manually scoring the participants' sketches in terms of *Stroke Quality* and *Shape Likeness*. For both metrics, we used two scorers to score all 432 sketches separately. To reduce potential bias, the scorers could not see the interaction methods while scoring and did not discuss the scores with others. Once the two scorers had scored the sketches, they compared all sketches of the same participant and compared each sketch to sketches with similar scores to increase inter-scorer reliability and standardized scores across participants. This evaluation method had been used in prior work [10, 39].
  - *Stroke Quality* We used Wiese et al.'s coding method [43], which evaluates each stroke in four categories: (1) *Line Straightness*, how straight and without 'waves' a stroke is, (2) *Matching of Two Lines*, whether strokes connect, (3) *Degree of Deviation*, how much two strokes on the same plane deviate, and (4) *Corrective Movements*, the extent of corrections at the end of the stroke to match another stroke. The scorer considered each category individually and scored them between 1 ("very poor") and 3 ("very good") for the whole sketching. As a sum of all four categories, each sketch received an *Overall Score* of 4-12.
  - *Shape Likeness* This qualitative score is based on the proportions of the 3D sketch compared to the 3D model, the deviation of each feature from the 3D model's features, and the presence and absence of shape features, i.e., missing, extra, and/or rotated elements. The scorer rated each sketch separately, between 1 (worst, no similarity) and 10 (best, high resemblance) relative to the 3D model as a reference. We determined the 'highest-scored' and 'lowest-scored' sketches by calculating the mean of *Shape Likeness* scores [10].
- *User Task Load* We used the *NASA Task Load Index (TLX)* [22] to evaluate the participants' perceived workload. This widely adopted subjective workload assessment tool measures six dimensions: *Effort*, *Frustration*, *Mental Demand*, *Performance*, *Physical Demand*, and *Temporal Demand*. We also used a paired-comparison procedure to obtain weights for each dimension, enabling the calculation of an overall workload score.

5 RESULTS

Results were analyzed using repeated measures (RM) ANOVA in SPSS and plotted using JMP. We considered data to have a normal distribution when Skewness (S) and Kurtosis (K) values were within ±1 [21]. *Task Completion Time* did not exhibit a normal distribution; thus, we log-transformed that data. Table 1 shows the RM ANOVA results for each factor. For brevity, we only report significant results here.

Table 1: Statistical analysis of the results. Statistically significant factors are shown in bold.

	Interaction Techniques	Sketching Depth
Task Completion Time	F(2, 22) = 0.69, p = 0.50, η^2 = 0.06, power = 0.15	F(1, 11) = 0.39, p = 0.54, η^2 = 0.03, power = 0.08
Shape Likeness	F(2, 22) = 0.91, p = 0.41, η^2 = 0.07, power = 0.18	**F(1, 11) = 1.54, p = 0.24, η^2 = 0.12, power = 0.20**
Line Straightness	F(2, 22) = 0.02, p = 0.97, η^2 = 0.00, power = 0.05	**F(1, 11) = 6.19, p <0.03, η^2 = 0.36, power = 0.62**
Matching of Two Lines	F(2, 22) = 3.28, p = 0.05, η^2 = 0.23, power = 0.56	F(1, 11) = 3.81, p = 0.07, η^2 = 0.25, power = 0.43
Degree of Deviation	F(2, 22) = 0.79, p = 0.46, η^2 = 0.06, power = 0.16	F(1, 11) = 0.00, p = 0.97, η^2 = 0.00, power = 0.05
Corrective Movements	F(2, 22) = 0.77, p = 0.47, η^2 = 0.06, power = 0.16	F(1, 11) = 3.14, p = 0.10, η^2 = 0.22, power = 0.36
Overall Score	F(2, 22) = 13.60, p = 0.39, η^2= 0.08, power = 0.19	**F(1, 11) = 4.92, p <0.04, η^2 = 0.30, power = 0.52**

5.1 Task Completion Time

We found a significant difference in *Task Completion Time* based on the drawn shape. Participants took significantly longer to complete the task when sketching a cube compared to a pyramid, $F(1, 11) = 137.365, p < 0.001, \eta^2 = 0.926, \text{power} = 1$ (4(a)). However, post-hoc (Bonferroni-corrected) pairwise comparisons revealed no additional significant differences across the remaining experimental conditions (selection methods and depth), indicating that shape was the primary factor influencing time.

5.2 Shape Accuracy

We found a significant difference in *Stroke Quality* — specifically in *Line Straightness*—–across two depth distances. Participants sketched straighter lines with fewer "waves" at 1 − 1.5 compared to 2 − 2.5 meters (Table 1 & Figure 4(b)). This suggests that increased depth makes sketching more difficult, affecting user precision and stroke consistency in 3D space. Indeed, as shown in Figure 4(c), line straightness declined at greater depths, highlighting the difficulties of maintaining accuracy in more distant strokes. However, interaction technique had no significant effect on shape accuracy, indicating that users maintained consistent sketching precision across all depth-selection methods.

5.3 User Task Load

A Friedman test revealed a significant difference in overall workload across the three interaction methods ($\chi^2(20, 18) = 56.163, p < 0.001$). Post-hoc Wilcoxon Signed-Rank tests indicated that the Gaze+Controller demanded significantly more *Effort* than the Ray-Cursor ($Z = -2.407, p < 0.016, r = 0.694$), and caused greater *Frustration* compared to the bi-manual method ($Z = -2.053, p < 0.040, r = 0.592$). *Mental Demand*, was lower for the uni-modal than multimodal method ($Z = -2.504, p < 0.012, r = 0.722$), while *Physical Demand* was notably higher for both bi-manual and multimodal relative to uni-modal ($Z = -2.627, p < 0.009, r = 0.758$)

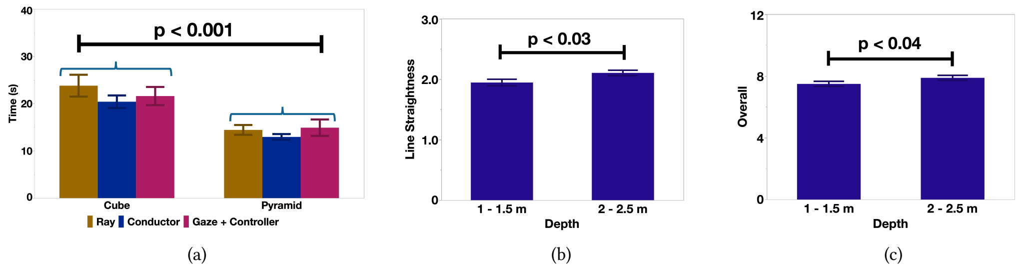

Figure 4: (a) Comparison of Task Completion Time between Cube and Pyramid Shape. Comparison of basic shape sketching at different depth (b) *Line Straightness* scores across depth distances. (c) Overall *Stroke Straightness* scores across depth distances.

and ($Z = -2.320, p < 0.020, r = 0.669$), respectively. A similar pattern emerged in *Temporal Demand*, where uni-modal again yielded a lower workload compared to multimodal ($Z = -2.310, p < 0.021, r = 0.666$) and bi-manual ($Z = -2.108, p < 0.035, r = 0.608$). Finally, overall workload was significantly higher for multi-modal compared to the uni-modal method ($Z = -2.353, p < 0.019, r = 0.679$), as shown in Figure 5.

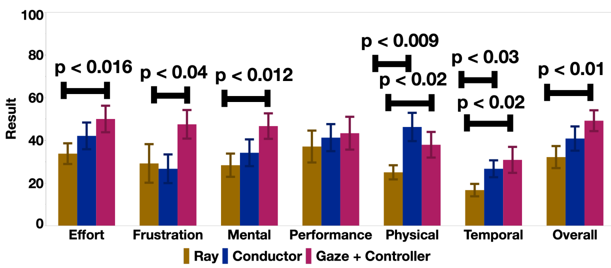

Figure 5: Comparison of NASA TLX workload dimensions across interaction techniques.

5.4 User Experience

Following the experiment, participants rated the depth selection techniques on a 5-point Likert scale, with 1 being "least preferred" and 5 being "most preferred." RayCursor method received the highest average rating (M = 4.58, SD = 0.79), indicating that participants found it the easiest method for selecting depth. The Conductor method followed with a slightly lower average rating (M = 3.5, SD = 1.09), suggesting that while it was effective for depth selection, it was perceived as more physically demanding. The Gaze+Controller method ranked last (M = 3.17, SD = 1.03), with participants noting that while it offered flexibility, it was less intuitive compared to the other method.

6 DISCUSSION

In this paper, we investigated three different interaction methods to select depth for Depth3DSketch. Overall, we found that participants were able to sketch the basic 3D shapes in all conditions without significant trade-offs. Among the evaluated methods, the RayCursor method — using a single controller with distance control — emerged as the most preferred technique with the least cognitive effort. Based on these results and past work [39], future 3D sketching techniques should leverage the simplicity of uni-modal interaction methods to control depth.

Regarding the Conductor method, although offering potentially precise depth selection via two controllers, it did not outperform RayCursor in user performance or preference, and participants regarded it as more physically demanding. While this is in some way an expected result — an additional hand is needed — the current study setup may not show us the entire picture for remote 3D sketching activities. The RayCursor method is a relative approach to adjust depth, which may not scale well for larger depth distances. Instead, the absolute pointing of two rays uses hand orientation — which can allow for more rapid switches of depth levels, e.g., in use cases when sketching large architectures like buildings or maps, which are interesting subjects for future studies.

Regarding the Gaze+Controller approach, combining gaze with controller input was the least preferred due to its complexity but similarly provides some further promise beyond our currently evaluated context. Coordinating the gaze ray with a controller ray is inherently subject to the trade-off of using the eyes as input vs. the perception of depth. Our initial approach to add visual feedback on the ground within the field of view helped users to perceive and select the right depth, but other methods, like a transparent plane, may allow us to further extend depth perception [41]. Moreover, participants reported a higher perceived workload for the multi-modal condition. A possible contributor is that most participants were novices with gaze-based interaction, which may have introduced additional cognitive load. Future investigations should explore training protocols or repeated sessions to determine whether user adaptation reduces perceived workload and affects final sketch quality.

We also identified that sketching further away was more challenging, as evidenced by the reduced line straightness at greater depths (2–2.5 m). This aligns with prior research [2, 9], which shows that increasing distance can compromise precision in 3D interactions. These results suggest opportunities to explore single-controller scaling methods [27] for 3D sketching, which might reduce the issues associated with such methods. Although the sketching technique remains the same after depth selection, the *method* used to choose depth can introduce variability in user performance. Each depth selection approach imposes distinct cognitive and motor demands, affecting the final sketch quality. For instance, Gaze+Controller requires coordinating eye and hand inputs, possibly increasing mental workload and leading to less stable strokes, while RayCursor offers a more controlled process, producing smoother lines. These differences may influence the placement of finer details or precise shapes, particularly when users must create steady, accurate strokes at extended distances. One alternative to direct distant sketching is a proxy space, where users sketch nearby and then project strokes to a far location, such as MobiSketch [26]. However, such approaches separate stroke creation from the already existing content, potentially hindering spatial alignment and depth awareness. Sketching nearby and then transferring content to a distant place also prevents direct placement relative to existing distant content—unless that content is duplicated close by, which adds complexity. In this work, we chose direct freehand sketching to see if users could adapt to beyond-arm-reach scenarios without sacrificing sketch quality.

Our study has several limitations that point to future work. In our experiment, participants mainly focused on the sketching part, which demonstrated that participants could relatively easily perform distant sketching, but that choice yielded fewer insights into the initial depth selection. Our study represents the first demonstration that users can sketch at two potential sketching depths. The next steps include investigations of longer continuous depth ranges and more frequent switching between different depths. In addition, the method focused on sequential depth specification and sketching sub-tasks, but further method explorations are needed to, e.g., support rapid depth changes for long-range sketches. Another area for exploration is how sketching depth might influence user preference for various interaction methods. Further, identifying threshold values, i.e., the maximum effective depth for optimal 3D sketching would help designers match interaction techniques to suitable distance ranges.

7 CONCLUSION

In this paper, we examined three depth selection methods—RayCursor, Conductor, and Gaze+Controller—for distant 3D sketching in virtual reality, called DEPTH3DSKETCH. Our findings indicate that RayCursor was the most effective and preferred technique, combining simplicity, ease of use, and lower cognitive and physical workload. While Conductor offered precise depth control using dual controllers, it did not outperform RayCursor and was more physically demanding. Gaze+Controller was the least preferred and had the highest cognitive load, yet it required only a single controller, suggesting potential for further refinement. These results highlight the importance of designing interaction methods that emphasize simplicity and ergonomic efficiency, particularly when targeting precision at greater depths. By addressing distance, modality integration, and user comfort factors, researchers can refine immersive sketching systems and foster more accessible, efficient, and engaging 3D sketching experiences.

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