EyeGuide & EyeConGuide: Gaze-based Visual Guides to Improve 3D Sketching Systems

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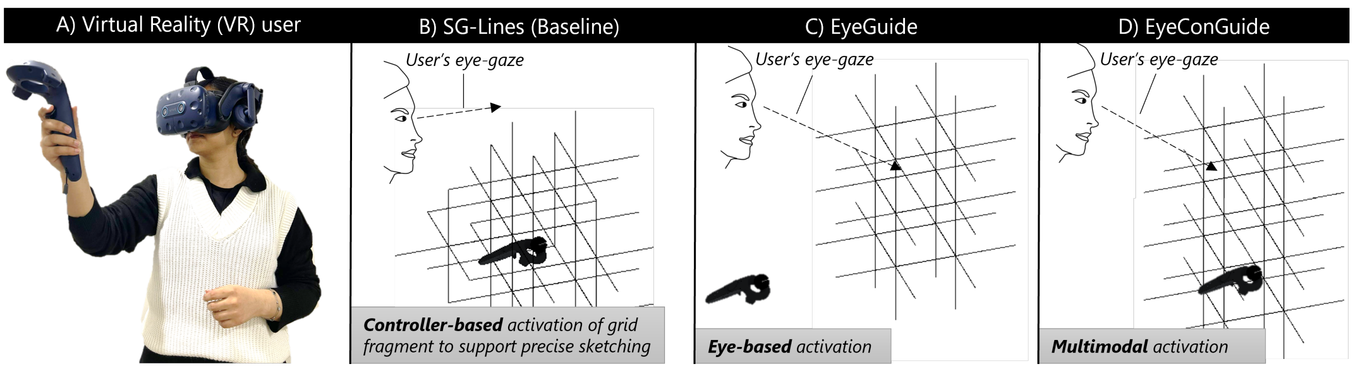


Figure 1: (A) Our work explores guided 3D sketching, a basis for precise free-form design in virtual reality productivity and creativity applications. (b) Previous studies showed that users can benefit from an adaptive grid system that follows the hand through the handheld controller. We investigate two concepts to render grid fragments based on eye-tracking (c, d). EyeGuide is an eyes-only method, and EyeConGuide combines the controller and gaze information to fade in/out the visual guide.

ABSTRACT

Visual guides help to align strokes and raise accuracy in Virtual Reality (VR) sketching tools. Automatic guides that appear at relevant sketching areas are convenient to have for a seamless sketching with a guide. We explore guides that exploit eye-tracking to render them adaptive to the user's visual attention. EyeGuide and EyeConGuide cause visual grid fragments to appear spatially close to the user's intended sketches, based on the information of the user's eye-gaze direction and the 3D position of the hand. Here we evaluated the techniques in two user studies across simple and complex sketching objectives in VR. The results show that gaze-based guides have a positive effect on sketching accuracy, perceived usability and preference over manual activation in the tested tasks. Our research contributes to integrating gaze-contingent techniques for assistive guides and presents important insights into multimodal design applications in VR.

CHI '24, May 11–16, 2024, Honolulu, HI, USA

ACM ISBN 979-8-4007-0330-0/24/05…$15.00
https://doi.org/10.1145/3613904.3641947

CCS CONCEPTS

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

KEYWORDS

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

ACM Reference Format:
Rumeysa Turkmen, Zeynep Ecem Gelmez, Anil Ufuk Batmaz, Wolfgang Stuerzlinger, Paul Asente, Mine Sarac, Ken Pfeuffer, and Mayra Donaji Barrera Machuca. 2024. EyeGuide & EyeConGuide: Gaze-based Visual Guides to Improve 3D Sketching Systems. In *Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI '24), May 11–16, 2024, Honolulu, HI, USA.* ACM, New York, NY, USA, 14 pages. https://doi.org/10.1145/3613904.3641947

1 INTRODUCTION

Virtual Reality (VR) 3D sketching combines the ease and flexibility of traditional 2D drawing with the depth and immersion of 3D environments. To accurately draw lines and shapes in mid-air, an auxiliary grid of lines can be displayed to visually align and orient the strokes when sketching. In the GravitySketch[1] 3D VR application, for example, users can activate a global 3D grid. Google Tiltbrush[2] allows the user to employ variable-shape guides which are manually positioned before using them to assist in drawing. These methods are based on a separation of concerns between manipulating and using the assistance. Our research investigates a complementary way of guided sketching, an adaptive sketching assistance that aims to provide visual guides implicitly through the human gaze as an indicator of interest.

Several research efforts have involved adaptive visual guidance [9, 26, 52, 58, 59]. The idea is to use dynamically-appearing grid fragments in relevant areas to be instructive and helpful when needed without the large and static visual occlusion of a fixed grid in the scene. For example, Barrera Machuca et al.'s Smart3DGuides [9] included SG-Line, an adaptive grid for VR in which visual guides activate at the the user's handheld controller position. This can increase sketching accuracy without penalizing performance, useful for instance to enhance the sketching experience for novices. However, while our hand guides our current drawing location, it does not always foresee our next sketching move.

With VR systems increasingly supporting eye-tracking technology, we explore combined eye and controller tracking as a new mechanism to control where a grid fragment appears in space for 3D sketching. Our eye movements are coupled in time and space with the actions of our hands, in particular when we draw. According to visuomotor studies of drawing, the eyes may follow the hand to assess its performance, guide the hand closely in manual work, or even be way ahead of the hand when planning future strokes [17, 25, 50]. Anticipatory eye movements play a key role in helping the user in 3D hand actions, indicating the potential to reveal information about where the user intends to sketch. VR applications can exploit such intricacies to dynamically present context-relevant information to the user. Unique challenges arise in the design of such dynamic mechanisms: the technical fusion of the spatio-temporal information of the eyes and hands on-line, at an ideal balance between providing informative visual assistance while minimizing distraction and information overload.

In this paper, we present two gaze-contingent techniques, called EyeGuide and EyeConGuide. They render relevant sketching grid fragments dynamically in distinct areas: (1) with EyeGuide, around the gaze area, and (2) with EyeConGuide, surrounding both the gaze and hand position (Figure 1). Both techniques are designed to gradually fade in visual grid fragments at relevant locations, with no manual input effort. With EyeGuide the gaze-based grid fragments appear at arm's distance in the gaze direction, whereas with EyeConGuide the position is based on the controller position in space and the presence of previously drawn strokes.

We present two user studies to investigate sketching performance, quality, and user experience of our proposals. The first focused on sketching basic shapes, such as lines and circles, and the second on complex shapes, such as a 3D model of a can opener. In both studies, we compared the proposed techniques to two baselines, one without visual guides and one with non-toggleable controller-based grid fragments. Our aim was to assess the new techniques' performance with regards to time and accuracy and better understand the qualitative user experience. Our results show for basic shapes, sketching with gaze-contingent techniques had higher line straightness and shape likeness than with both baseline guides. We also found that EyeGuide exhibited lower *Shape Deviation* than EyeConGuide, yet participant preference was the opposite (35% of users preferred EyeConGuide while 17.8% of users preferred EyeGuide). For complex shapes, we found that EyeGuide had higher shape likeness than both baselines, and that participants preferred gaze-contingent techniques than the baselines.

Participants ranked the eye-gaze-based techniques higher than the other two evaluated methods, and EyeConGuide scored best on the SUS questionnaire ('B'), indicating good quality. These results show that adding eye-gaze as an adaptation medium for 3D sketching guides can increase sketching accuracy without compromising performance while enhancing its usability compared to existing hands-only adaptations. This has relevance for the present and future, as it points to integrating our proposed guides into current design applications and exploring contextual information further — even beyond eye and hand tracking, in order to push the boundaries of the user's spatial understanding and elevate the practice of 3D sketching.

In summary, the contributions of this research are:

- A new concept for interaction guidance methods based on the user's gaze, where a grid fragment dynamically appears depending on the gaze and controller position.
- Two new gaze-based multimodal interaction techniques for adaptive grid fragments in 3D sketching: EyeGuide and EyeConGuide.
- Two user studies with basic and complex shapes to identify the effect of gaze-based interaction techniques on performance, usability, and dependence on the user's spatial abilities. We found that eye-gaze techniques are easy to use, that they provide more accurate sketches, and that users prefer them over manual methods.

2 RELATED WORK

2.1 3D Sketching

Despite the advantages of 3D sketching, correctly positioning a stroke in 3D space is challenging as users are affected by high sensorimotor [55] and cognitive [8, 39] demands, depth perception issues in stereo displays [7, 10, 11], and the absence of physical support [2].

[1] https://www.gravitysketch.com
[2] https://www.tiltbrush.com

Previous work studied the control and ergonomic aspects of sketching in midair [2, 34] and the learnability of 3D sketching [8, 55] to identify the cause(s) of these inaccuracies. Here, we aim to reduce the effect of higher sensorimotor and cognitive demands and depth perception issues onto 3D sketching by adding visual support inside the virtual environment.

Work addressing these issues has proposed novel interaction devices and techniques for 3D sketching [4]. Examples include pens [23, 44, 54] and virtual [1, 5, 35] or physical [20, 32] surfaces that emulate the presence of a drawing surface. Other work aims to reduce the sensorimotor and cognitive demands through beautification [5, 24] or novel metaphors to create strokes [31, 32, 45]. Finally, another approach uses visual guides to improve the user's *Shape Accuracy* [9, 26, 59]. One limitation of these approaches is that they mostly focus on interaction with controllers or gestures. In contrast, we use gaze to implicitly control visual guides.

2.2 Eye-Hand Coordination in Drawing

For real-world 2D drawing, a body of visuomotor studies explored user eye-hand coordination behaviors and provided relevant insights. Sun et al. [49] recorded participants' eye movements to analyze sketch perception and to identify how designers create new ideas. They found that users exhibit distinct eye movements when drawing 2D shapes. Tschalenko et al. [50] found that in eye-pursuit behavior, the user closely follows their hand with their eyes. In contrast, in anticipation behaviors, the eyes often look ahead to future hand targets. Users also use specific eye-scan paths, where they focus only on the parts of the object they are drawing and follow a scan path that resembles an edge-following pattern along image contours [17]. Finally, there are differences in the eye movement characteristics between tracing and drawing, as tracing demands continual comparison between the line to be traced and the pen tip, while drawing involves look-ahead eye movements [25].

Turkmen et al. [52] studied eye-hand coordination when drawing over two different styles of *static* visual guides (continuous and segmented) in VR. They found that the eyes fixate mainly close to the pen cursor when following a continuous guide. In contrast, a segmented guide led to the eyes more frequently switching between fixating on the cursor and the guide. This suggests that the eyes can indicate where the user may draw and where guides might be helpful.

2.3 Gaze-based Design

The characteristics of eye-gaze provide novel opportunities for gaze-responsive interaction techniques. Previous work on eye-gaze in VR interfaces shows that it enables faster actions for various tasks [12], since gaze can reach up to 900 degrees/second [3] movement speed, also requiring less muscle movement and thus energy [48]. Gaze also makes user interfaces more accessible [43].

Our work builds upon gaze-contingent and Attentive User Interfaces (AUIs), i.e., computer interfaces that dynamically adapt the display content to the user's attention [53]. These interfaces utilize eye-tracking information to implicitly provide contextual interactions, such as warping the mouse cursor to the area of the user's gaze [60]. However, such attentive interface controls have been rarely considered in sketching and even less in 3D. For 2D drawing, Jowers et al. [33] used gaze to identify the user's intention when creating a new shape.

Several research efforts employed gaze to modulate and contextualize stylus input on a tablet, affording the rapid switch of drawing modes [30, 40]. Chen et al. projected eye-gaze patterns recorded while a user looked at a drawing subject onto the drawing canvas to provide a visual memory aid of what to draw [16]. In VR, multimodal eye gaze and gestural UIs can afford novel interaction styles that advance the user's manual input capabilities [41]. In the context of 3D modelling, gaze and gestures allow manipulating objects from afar as demonstrated in use cases of interior design [41, 57]. For design and 3D sketching in VR, previous work proposed assisting the user in gaze-based mode switching during sketching to allow users to leave the pen at a comfortable position [42] and to directly apply parameters to objects through a gaze-based see-through tool [37]. Despite the advantages of gaze-based interaction, like being hands-free, implicit, and highly dynamic [12], there is little investigation on integrating eye-tracking into 3D sketching and specifically to address sketching accuracy issues.

3 VISUAL GUIDES

3.1 State of the Art

From the literature review, we identified that controller-based guidelines are the most common ones. One such example is SG-Line [9], where the grid fragment follows the position of the controller in VR when the user is not drawing (Figure 2(a)). When the user draws, the grid fragment displayed starts at the stroke start position and extends to the controller position. When evaluating SG-Line, Barrera Machuca et al. [9] found that they increase user sketching accuracy.

3.2 Proposed Visual Guides Design

We propose EyeGuide and EyeConGuide, two visual guides for VR that the user controls with their gaze, illustrated in Figure 2(b) and (c), respectively. These guides are purely visual and non-constraining to avoid affecting the user experience. The resulting stroke thus follows the controller position without straightening, snapping, or other modifications, affording the user free 3D sketching abilities while reducing their cognitive load and the potential for errors. In this work, we also implemented the controller-based SG-Line guides [9] to compare to our proposed methods (Figure 2(a)).

All our guide conditions rely on a global 3D grid that is fixed in the virtual drawing space, and we display only a fragment of it depending on the evaluated technique. In our system, the underlying grid consists of 20 cm cubes, and we only display grid lines with an endpoint within 30 cm of a reference point or segment. This distance limit prevents displaying an infinite grid, which would be visually too dense. Also, to avoid having lines point directly at the user's face, we do not render lines if they are too close to the user or point directly into the direction of the user's eyes. Next, we describe each evaluated interaction technique:

EyeGuide: The grid fragment is shown in the user's eye-gaze direction, whether the user is drawing or not (Figure 2(b)). The displayed grid fragment is centered at a point 75 cm away (approximately arm's length) from the user along the gaze vector.

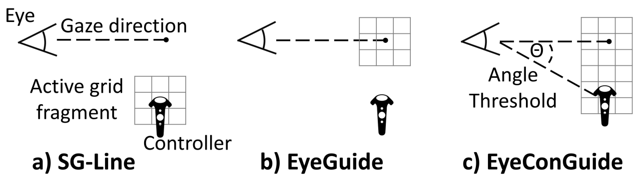


Figure 2: The basic adaptation mechanism for the grid fragment appearing in the different eyes and controller-based techniques. While the grid fragment follows the controller position in SG-Line (a), it follows the gaze direction in EyeGuide (b). For EyeConGuide (c), the grid fragment follows the drawing state and whether the controller and other strokes are visible.

EyeConGuide: The grid fragment displayed depends on the state (drawing or not) and whether the controller and other strokes are visible or not. Figure 3 summarizes the logic. We first explain the four cases when the user is not drawing (see the next paragraph for drawing actions). When neither the controller nor the strokes is visible, the grid fragment follows the eye movement of the user at a fixed distance, as for EyeGuide. When the controller is visible, but no strokes are visible, the grid fragment is shown at the controller position and extended to include the point along the gaze direction that is at the same distance as the controller (Figure 4(a)). When the controller is not visible, and some strokes are visible, the grid fragment follows the eye movement at a depth of the visible stroke closest to the user (Figure 4(b)). When both the controller and strokes are visible, the grid fragment is shown at the closest stroke to the controller and extended to include the point along the gaze direction that is at the same distance as the stroke (Figure 2(c) and 4(c)).

When a user is drawing with EyeConGuide, the grid fragment starts at the stroke's start position and extends to a point in the gaze direction at the same distance as the start position. During sketching, the controller position does not affect the guide extension, which allows users to "follow" the lines of the guide with their stroke (Figure 4(c)). Finally, to enhance the user experience, we implemented fade-in and fade-out for the appearance of grid fragments so that they smoothly blend in/out rather than suddenly appearing or disappearing. As shown in Figure 4, the grid's opacity varies in different conditions. Grid fragments within the area of interest fade in within approximately three frames ($\sim 33ms$), and grid fragments no longer in the area of interest fade out within about five frames ($\sim 55ms$). Here, we assumed an average frame rate of 90 FPS to calculate the time. We heuristically determined these values with a pilot study.

We implemented our interaction techniques in a system running on an 11^{th} Gen 2.5 GHz Intel(R) Core(TM) i7-11700F desktop PC with 32 GB RAM and an NVIDIA GeForce GTX 3070 graphics card. As a VR headset, we used an HTC VIVE Pro Eye with its controllers. We provided participants with a 4 m x 4 m drawing area free of obstacles. For the virtual environment, we used Unity version 2020.3.21f1. The HTC VIVE Pro Eye has a Tobii eye-tracker integrated, a native Tobii XR Unity package, and calibration software called VIVE SRanipal SDK[3]. In our system, we directly retrieve the gaze ray direction from the Tobii XR library and then use a 1€ filter [14] to stabilize it. In our system, we then use the origin point (3D vector) of the gaze ray from Tobii XR and the stabilized gaze ray direction as the gaze ray.

4 RESEARCH QUESTIONS AND METHOD

Given the proposed techniques, we formulate the following research questions (RQs):

- **Performance (RQ1)**: Do gaze-based guides (EyeGuide and EyeConGuide) improve user performance (time) and accuracy (*Stroke Quality* and *Shape Likeness*)? To understand the pros and cons and the effect of the proposed techniques on the users' interaction behavior, this research question centers around the physical act of making a stroke, for which measuring motor performance and eye-hand coordination are central.
- **Usability (RQ2)**: How do gaze-based guides affect the usability and the perceived workload? The gaze-based guides will help users focus on their 3D sketching performance while providing intuitive visual cues, thereby potentially reducing cognitive load and improving overall user experience and system usability. By measuring the users' perceived usability of the techniques, we complement the quantitative performance evaluation.
- **Spatial ability (RQ3)**: Does the spatial ability of the user influence how gaze-based guides affect their performance while sketching? During 3D sketching, people use their spatial abilities to envision objects in 3D [39], perceive their spatial arrangement [21], and imagine the eventual appearance of the object [18], which are all abilities related to the spatial visualization skills of a person. Previous work found that the user's spatial ability affects drawing performance [8, 9], and we extend the knowledge by studying how it interacts with multimodal visual guides.

Our research questions are explored across two experiments to provide complementary perspectives and allow a more complete assessment of the proposed methods' efficiency.

- **Study 1 — Basic Shapes**: Study 1 focuses on basic shapes that can be completed in one stroke. This fundamental investigation of sketching allows capturing the effects on low-level straight and curved shape properties. Our work extends prior knowledge of the properties of such tasks [2, 34] and gaze behaviors [52] through a study of novel visual guides.
- **Study 2 — Complex Shapes**: Study 2 focuses on the more realistic task of sketching complex shapes that involve multiple distinct strokes in succession. This allows us to gain insight into the performance of the visual guide over time with more natural and varied motor operations, as well as to assess how guides help users in the planning phase of the 3D sketching process [6]. In particular, users plan individual strokes that establish the whole sketch, and visual guides aid them in visualizing the relationships between strokes,

[3]https://developer.tobii.com/xr/develop/xr-sdk/getting-started/vive-pro-eye

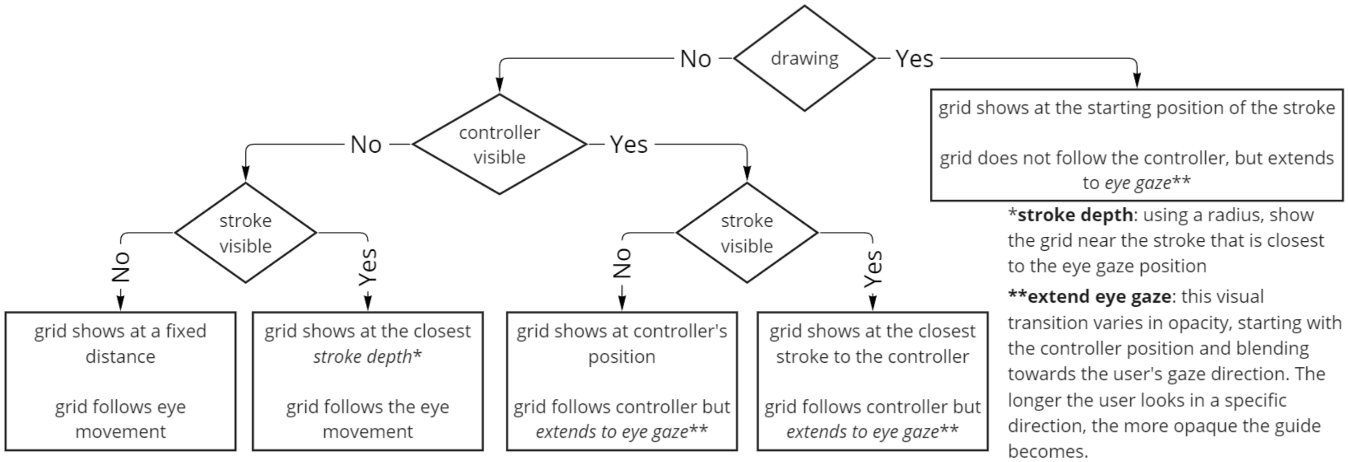


Figure 3: Decision tree of the grid positioning method for EyeConGuide.

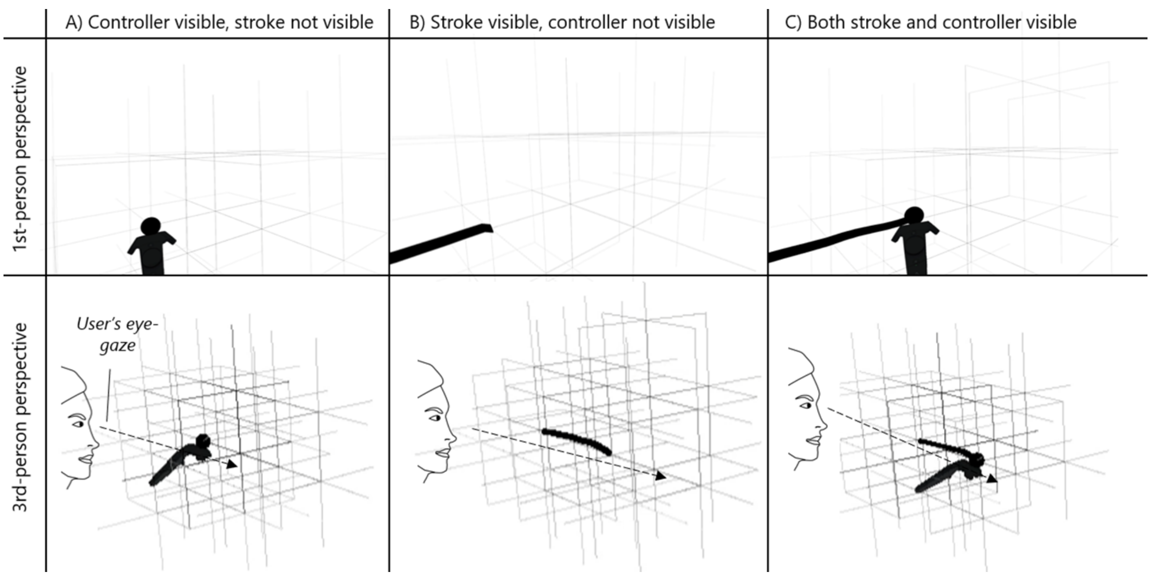


Figure 4: Details of the grid positioning method for EyeConGuide when the user is not sketching

identifying the distances between strokes, and making better decisions about the starting and end positions of each new stroke. Moreover, previous work has used complex shapes, i.e., 3D objects, to evaluate a tool's capability to draw specific shapes [19] or its usability [9].

5 STUDY 1 — BASIC SHAPES

In our first study, we investigated the effect of the gaze as an assistive system for two basic shapes, a line and a circle (Figure 5), to explore both RQ1 and RQ2. Also, as these shapes were studied previously [52], this approach enables a comparison of the effectiveness of the proposed system to previous work.

5.1 Methodology

5.1.1 Participants. We recruited sixteen participants (11 male, 5 female) from the local university. Their ages ranged between 19 and 31 (M = 21.4, SD = 2.71). All were right-handed except for one. Four participants had never experienced VR, five fewer than five times, and the other seven had experienced it more than five times. Fourteen participants reported having no experience sketching in VR and two had participated in prior VR user studies related to 3D sketching. Finally, thirteen participants reported not using sketching programs regularly, and three reported using them at least once a week.

5.1.2 Evaluated Interaction Techniques. We evaluated EyeGuide and EyeConGuide. We also include two techniques as baseline conditions: SG-Line, and No Guide without any assistive sketching grid.

5.1.3 Experimental Design. We used a four-factor within-subject design with four **Visual Guides** (4_{VG} = EyeConGuide, EyeGuide, No Guide, and SG-Line), two basic **Shapes** (2_{Sh} = line and circle), with two **Shape Orientations** (2_{SO} = vertical and horizontal) and two **Shape Sizes** (2_{SS} = 60 and 110 cm). We chose these two object sizes as the 60 cm objects were always visible while drawing, whereas the 110 cm ones extended outside the field of view, requiring the participants to rotate their heads. To show participants where and how large their sketches should be (i.e., communicating which drawing they should complete with no verbal or written cues), we showed small semi-transparent "reference" spheres in the environment as in Figure 5. Each participant performed ($2_{Sh} \times 2_{SO} \times 2_{SS}$ =) 8 drawings (8_{Dr}) with 4 visual guides (4_{VG}), leading to ($8_{Dr} \times 4_{VG}$ =) 32 Conditions (32_{Co}). Each participant repeated each condition three times, resulting in ($32_{Co} \times 3_{rep}$ =) 96 trials (96_{tr}) for each participant and ($96_{tr} \times 16_{part}$ =) 1536 total drawings. The order of all conditions was counterbalanced to reduce learning effects.

5.1.4 Procedure. Upon arrival, participants completed a preliminary questionnaire about their demographics and prior VR and drawing experience. The experimenter introduced them to the study, instructed them to use their dominant hand, assisted them in putting the VR headset on and running the eye tracker calibration, and adjusted the height of the virtual workspace to their eye level. Then, participants started drawing the two basic strokes with varying sizes and orientations, where the desired size and orientation were indicated by guidance spheres. For each line, two guidance spheres indicated the start and end points for the strokes, while for each circle, four guidance spheres indicated points that the stroke should pass through, as shown in Figure 5. The guidance spheres' positions were at grid intersections, not at grid lines. These guidance spheres removed the need for participants to estimate the size/scale of the shapes and their orientation and help standardize the size of the drawn strokes. After completing all 96 trials, the participants filled out a post-experiment questionnaire, where they reported their preferences on guide conditions and rated their experience.

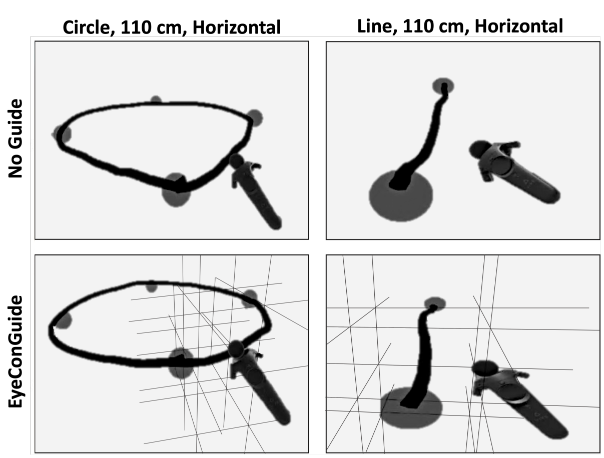
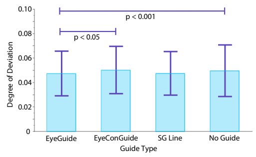


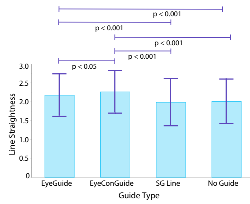
Figure 5: Guidance spheres and example basic shapes drawn in Study 1.

5.1.5 Evaluation Metrics. Following previous work by Barrera Machuca et al. [6], we recorded and analyzed the following measures:

- *Task Completion Time:* The time from when a participant first pressed the controller button, which initiated the drawing for a given trial, until the last time they released the button. We used this metric to compare task performance between different UIs.
- *Shape Deviation*: For this evaluation metric, we computed the average shortest distance from each vertex of the user's stroke to the target shape. This metric quantifies the distortion of the sketch shape, and we use it to identify differences between the perfect and drawn shapes automatically. More specifically, we calculated the *Shape Deviation* as follows: because participants drew a stroke using the sphere as guides, each stroke already had a similar length and starting position. Still, we further normalized them to have the same starting position and size. Then, using the start position and the stroke's local transformation, we calculated a perfect shape with the same number of vertices. Finally, we calculated the difference between the perfect and drawn vertices, then averaged this distance to get the *Shape Deviation.*
- *Shape Accuracy*: We measured the user accuracy by manually scoring the participants' drawings in terms of *Stroke Quality* and *Shape Likeness.* For both metrics, we used three raters (two authors and a researcher who was not involved in this experiment) to score all 1536 (4_{VG} x 2_{Sh} x 2_{SS} x 2_{S0} x 16 participants x 3 repetitions) drawings separately. To avoid bias, the raters could not see the guide type while scoring and did not discuss the scores with others. Once the three scorers had scored the drawings, we compared all drawings of the same participant and compared each sketch to sketches with similar scores to increase inter-rater reliability and standardized scores across participants. This evaluation method had been used in prior work [9, 15, 38, 51]. Next, we describe the data collected (note that not all measurements apply to the simple strokes in this study):
  - *Stroke Quality* We used Wiese et al.'s [55] coding method, 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 each between 1 (very poor) and 3 (very good) for the whole drawing. As a sum of all four categories, each drawing received an *Overall Score* of 4-12.
  - *Shape Likeness* This is a qualitative score based on the proportions of the 3D drawing 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 drawing separately, between 1 (worst, no similarity) and 10 (best, high resemblance) relative to the 3D model as a



(a)



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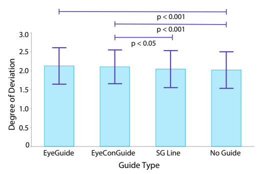

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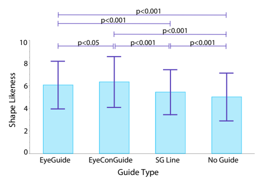


(d)

Figure 6: Study 1 result plots for basic shape sketching with different visual guide types: (a) *Shape Deviation* showing significantly less deviation while sketching for EyeGuide and EyeConGuide. (b) *Line Straightness* increases with EyeGuide and EyeConGuide. (c) *Degree of Deviation* increases with EyeGuide and EyeConGuide. (d) *Shape Likeness* increases with EyeGuide and EyeConGuide. Error bars show the standard deviation of data. Post-hoc analysis results are shown in purple lines at the top.

reference. We determined the highest-scored and lowest-scored sketches for each visual guide by calculating the mean of *Shape Likeness* scores [9].

5.2 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 [27]. *Task Completion Time* and *Shape Deviation* did not exhibit a normal distribution; thus, we log-transformed their data. Table 1 shows the ANOVA results for each factor. For brevity, we only report significant results here; the remainder of the analysis, including the interactions between conditions, can be found in the supplementary materials.

5.2.1 Task Completion Time. There was no significant difference in *Task Completion Time* for visual guides. As expected, we found a significant difference in *Task Completion Time* for shape (participants were faster while sketching lines than circles), size (participants were faster while sketching smaller strokes (60 cm) than larger ones (110 cm)), and orientation (participants were faster while sketching vertically than horizontally).

5.2.2 Shape Deviation. There was a significant difference in *Shape Deviation* for visual guides (Figure 6(a)). Participants exhibited less deviation while sketching with EyeGuide than No Guide and EyeConGuide. We also observed significant difference results in shape (participants exhibited less deviation while sketching lines than circles) and orientation (participants exhibited less deviation while sketching horizontally than vertically) for *Shape Deviation*.

Table 1: Study 1 RM ANOVA results for the measures. Statistically significantly different factors are shown in bold.

	Visual Guide (VG)	Size	Shape	Orientation
Task Completion Time	$F(3, 45) = 1.99$, $p = 0.128$, $\eta^2 = 0.12$ power = 0.67	**$F(1, 15) = 212.79$, $p < 0.001$, $\eta^2 = 0.93$ power = 1**	**$F(1, 15) = 88.60$, $p < 0.001$, $\eta^2 = 0.85$ power = 1**	**$F(1, 15) = 20.53$, $p < 0.001$, $\eta^2 = 0.58$ power = 0.98**
Shape Deviation	**$F(3, 45) = 4.62$, $p = 0.007$, $\eta^2 = 0.23$ power = 0.86**	$F(1, 15) = 2.19$, $p = 0.16$, $\eta^2 = 0.13$ power = 0.28	**$F(1, 15) = 17.02$, $p = 0.001$, $\eta^2 = 0.53$ power = 0.97**	**$F(1, 15) = 0.41$, $p = 0.02$, $\eta^2 = 0.31$ power = 0.67**
Line Straightness	**$F(3, 45) = 45.097$, $p < 0.001$, $\eta^2 = 0.750$ power = 1**	**$F(1, 15) = 27.667$, $p < 0.001$, $\eta^2 = 0.648$ power = 0.998**	**$F(1, 15) = 57.731$, $p < 0.001$, $\eta^2 = 0.794$ power = 1**	**$F(1, 15) = 1.895$, $p < 0.001$, $\eta^2 = 0.112$ power = 0.252**
Degree of Deviation	**$F(3, 45) = 11.577$, $p < 0.001$, $\eta^2 = 0.436$ power = 0.985**	**$F(1, 15) = 71.689$, $p < 0.001$, $\eta^2 = 0.827$ power = 1**	$F(1, 15) = 3.504$, $p = 0.081$, $\eta^2 = 0.189$ power = 0.418	$F(1, 15) = 2.977$, $p = 0.105$, $\eta^2 = 0.166$ power = 0.365
Shape Likeness	**$F(3, 45) = 89.407$, $p < 0.001$, $\eta^2 = 0.856$ power = 1**	**$F(1, 15) = 8.853$, $p = 0.009$, $\eta^2 = 0.371$ power = 0.794**	**$F(1, 15) = 71.675$, $p < 0.001$, $\eta^2 = 0.827$ power = 1**	**$F(1, 15) = 10.970$, $p = 0.005$, $\eta^2 = 0.422$ power = 0.872**

5.2.3 Shape Accuracy. For *Stroke Quality*, there was a significant difference in *Line Straightness* for visual guides (Figure 6(b)). The participants were able to draw strokes that were straighter with fewer 'waves' with EyeGuide and EyeConGuide than with SG-Line and No Guide. We also observed significant difference results in size (participants drew smaller shapes straighter with fewer 'waves' than larger shapes), shape (participants drew straighter with fewer 'waves' lines than circles), and orientation (participants drew straighter with fewer 'waves' horizontal sketches than vertical ones) for *Stroke Quality*.

There was also a significant difference in the *Degree of Deviation* for visual guides (Figure 6(c)). The participants had less deviation with EyeConGuide than the base conditions and less with EyeGuide than No Guide. There was also a significant difference in size (participants drew more deviated circles than lines) for *Degree of Deviation*.

There was a significant difference in *Shape Likeness* for visual guides (Figure 6(d)). Participants drew more accurate shapes with EyeGuide and EyeConGuide than the baseline conditions, but in general, they were more accurate with EyeConGuide. There was also a difference between SG-Line and No Guide. Finally, we observed significant difference results in size (smaller shapes were more accurate than large), shape (lines were more accurate than circles), and orientation (horizontal was more accurate than vertical) for *Shape Likeness*.

5.2.4 User Experience. After the experiment, we asked the participants which guide they preferred. Five participants preferred EyeConGuide, indicating that this guide felt more realistic and compatible with sketching. Five participants preferred SG-Line, indicating that this guide followed their hand movements better while sketching. Four participants preferred No Guide, mentioning that this guide provided an empty environment to draw. Finally, two participants preferred EyeGuide, stating that using head movements helped them control the guides and gave them a better view of the sketch.

5.3 Discussion

In our first user study, we evaluated the user performance and user experience of the proposed gaze-based guides with two simple shapes.

Regarding RQ1, we did not observe a significant difference between visual guides regarding sketching time. A potential explanation for the temporal indifference compared to SG-Line is that the basic shapes are not sufficiently challenging to observe performance differences, which we follow up on in the second experiment. As a side note, in line with with prior work [2, 45] we find that participants took longer and were less accurate while sketching circles because they needed to carefully control their movement rather than simply moving in a straight line.

We also gained additional insights from the results of the *Shape Deviation* and *Shape Accuracy* analysis. For *Shape Deviation*, participants sketched the basic shapes more accurately with EyeGuide than EyeConGuide. This can suggest that unimodal interaction is sufficient for tasks where the user has to perform a single stroke, and having to do more to, e.g., activate the grid, may hinder the task. As well, we can confirm the prior art's finding that visual guides can improve the sketching accuracy over no-guide, as EyeGuide has led to lower *Shape Deviations*. On the other hand, the *Shape Accuracy* results and the user experience results indicate the multi-modal interaction (EyeConGuide, e.g., eye-gaze & controller) allowed participants to control the guides more in terms of *Line Straightness* and *Shape Likeness* than using only the unimodal (eye-gaze) interaction.

To enable us to compare our results with previous work on the efficiency of visual guides [2] and gaze behaviors [52], we focused on two basic shapes in the first user study. To extend our knowledge on the efficiency of visual guides and gaze behaviors toward the drawing of complex objects, we conducted a second study.

6 STUDY 2 — COMPLEX SHAPES

This study investigates whether visual guides affect user performance (RQ1) and the user experience (RQ2) while sketching two complex 3D shapes (Figure 7). Shape 1 is a bottle opener that requires users to draw curves and straight lines. The complexity of this object comes from the need to draw curves and two circles, one aligned on top of the other. Shape 2 is a geometrical shape that only requires straight lines. The complexity of this object lies in the correct orientation and length of each arm. Although the two shapes look different, they both need the participants to utilize similar skills to plan their actions, like drawing parallel strokes at different depth levels, and maintaining proportions between strokes. This second shape was also used by Barrera Machuca et al. [9]. Finally, based on findings from previous work about the effect of spatial ability on the 3D sketching performance for complex shapes [8, 9], we divided our participants into groups with high and low spatial abilities to also investigate the potential corresponding differences in our user study (RQ3).

6.1 Methodology

6.1.1 Participants. We recruited sixteen participants (9 male, 7 female) from the local university. Their ages ranged between 19 to 34 (M = 26.375, SD = 7.42). All participants were right-handed except for one. Among all participants, two reported drawing (physically or digitally) every day, one weekly, one twice a month, two once a month, three on three occasions, and seven never. Participants who had joined the first experiment were not allowed to attend the second one to eliminate potential learning effects and experimental bias. To evaluate their spatial abilities, each participant completed the VZ-2 Paper Folding test [22] prior to the experiment. The VZ-2 Paper Folding test evaluates the spatial visualization and reasoning abilities of a person. The ability to mentally manipulate and comprehend spatial visualization relationships, as assessed by this test, provides a foundation for effective 3D sketching. Similar to previous work [8, 9], we divided participants into two groups based on their VZ-2 scores: the ones with test scores higher than 15 out of 20 were considered to have High Spatial Abilities (HSA), and the rest to have Low Spatial Abilities (LSA). We recruited participants strategically to ensure that the two groups had equal numbers of participants (i.e., 8 HSA participants and 8 LSA participants). Since Study 2 was designed to investigate how people plan while sketching complex shapes, this test allowed us to assess the corresponding skill level of each participant.

6.1.2 Experimental Design. We designed a two-factor within-subject study with four **Visual Guides** (4_{VG} = EyeConGuide, EyeGuide, No Guide, and SG-Line), two **Object Shapes** (2_{OS} = shape 1 and shape 2), and a between-subject independent variable based on the participants' **Spatial Abilities** (2_{SA} = high and low). Each participant drew two shapes with four visual guides ($2_{OS} \times 4_{VG} = 8$ drawings each), which resulted in ($8_{Dr} \times 16_{part}$) 128 drawings in total. The order of conditions across within-subject dimensions was counter-balanced using a Latin Square.

6.1.3 Procedure. Upon arrival, we asked the participants to perform the VZ-2 paper-folding test, followed by a pre-experiment questionnaire about their demographics, sketching experience, and experience with VR and 3D sketching systems. Then, they put the VR headset on and calibrated the eye-tracking system before starting the tasks. All participants drew each shape a single time with all four visual guides using their dominant hand. Upon completing one condition, participants answered questions related to that condition. After completing all eight trials (4 Visual Guides conditions with one repetition for two Object Shapes each), the participants completed a post-experiment questionnaire about their experience and preferences. The experiment took approximately 60-90 minutes for each participant, including questionnaires and tests.

6.1.4 Evaluation Metrics. As in the first study, we included *Task Completion Time* and *Shape Accuracy* as metrics. We did not include *Shape Deviation*, as we did not find a standard method to accurately calculate the *Shape Deviation* for the complex shapes we used. Moreover, the difference between the participants' sketches was much too large to simply use an extended version of the same method as we had used in Study 1. The second and fourth rows in Figure 7 show illustrative examples of the vast differences among the created shapes, where the strokes vary greatly in number, orientation, and how well they complete the whole shape. For the *Shape Accuracy* metrics, we asked three raters (two authors and a researcher who was not involved in this experiment) to score all 128 (4_{VG} x 2_{OS} x 16 participants) drawings separately for *Stroke Quality* and *Shape Likeness*. Similar to Study 1, we compared all drawings of the same participant and compared each sketch to sketches with similar scores to increase inter-rater reliability and standardized scores across participants.

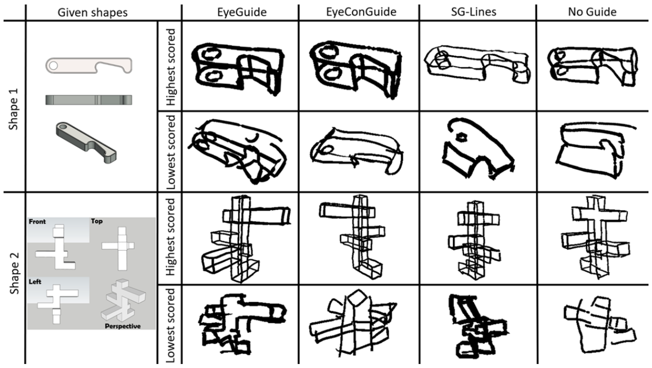


Figure 7: Study 2 tasks: The two complex 3D shapes participants were asked to draw. For illustration, the highest-and lowest-scored exemplar drawings by participants are presented for each condition.

Table 2: Study 2: Statistical analysis of the results. Statistically significant factors are shown in bold.

	Visual Guide (VG)	Spatial Ability (SA)	VG x SA
Task Completion Time	$F(3, 42) = 0.73$, $p = 0.54$, $\eta^2 = 0.05$, power = 0.19	$F(1, 14) = 1.94$, $p = 0.18$, $\eta^2 = 0.40$, power = 0.25	$F(3, 42) = 1.76$, $p = 0.17$, $\eta^2 = 0.11$, power = 0.43
Shape Likeness	**$F(3, 42) = 16.24$, $p < 0.001$, $\eta^2 = 0.54$, power = 1**	**$F(1, 14) = 6.14$, $p < 0.05$, $\eta^2 = 0.3$, power = 0.24**	$F(3, 42) = 0.96$, $p = 0.42$, $\eta^2 = 0.64$, power = 0.85
Line Straightness	**$F(3, 42) = 6.01$, $p < 0.01$, $\eta^2 = 0.30$, power = 0.94**	$F(1, 14) = 3.87$, $p = 0.07$, $\eta^2 = 0.22$, power = 0.45	$F(3, 42) = 1.32$, $p = 0.28$, $\eta^2 = 0.09$, power = 0.33
Matching of Two Lines	**$F(3, 42) = 5.59$, $p < 0.01$, $\eta^2 = 0.28$, power = 0.92**	$F(1, 14) = 1.47$, $p = 0.24$, $\eta^2 = 0.09$, power = 0.20	$F(3, 42) = 0.14$, $p = 0.93$, $\eta^2 = 0.010$, power = 0.07
Degree of Deviation	**$F(3, 42) = 6.51$, $p = 0.001$, $\eta^2 = 0.32$, power = 0.96**	**$F(1, 14) = 5.84$, $p < 0.05$, $\eta^2 = 0.29$, power = 0.61**	$F(3, 42) = 0.41$, $p = 0.75$, $\eta^2 = 0.03$, power = 0.12
Corrective Movements	**$F(3, 42) = 8.15$, $p < 0.001$, $\eta^2 = 0.37$, power = 0.99**	$F(1, 14) = 0.79$, $p = 0.40$, $\eta^2 = 0.05$, power = 0.13	$F(3, 42) = 0.14$, $p = 0.93$, $\eta^2 = 0.01$, power = 0.07
Overall Score	**$F(3, 42) = 13.60$, $p < 0.001$, $\eta^2 = 0.49$, power = 1**	$F(1, 14) = 3.46$, $p = 0.08$, $\eta^2 = 0.20$, power = 0.41	$F(3, 42) = 0.22$, $p < 0.88$, $\eta^2 = 0.02$, power = 0.94

In addition, we also included user experience evaluation questionnaires to better understand the usability of the proposed interactions. We employed the *System Usability Survey (SUS)* [13], which measures how usable guides are, on a scale of 1 (very poor) and 7 (excellent). We also used the *NASA Task Load Index (TLX)* [28, 29] to measure mental, physical, and temporal demand, as well as effort, frustration/failure, and performance (scale of 1 (very low) to 7 (very high)). *User preference* was measured by asking participants to rank the visual guides from 1 (least preferred) to 4 (most preferred). Finally, we solicited user comments on guide preferences and reasons.

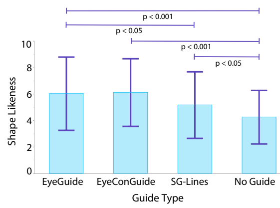
6.2 Results

We initially analyzed the results by shape, yet we saw no difference (see supplementary materials) in terms of accuracy measures. We hypothesize this is the result of both shapes having (overall) similar difficulty, as users need to utilize the same skills to plan them. Thus, we collapsed this factor by averaging the results of the two shapes. There was a difference in task time, but this is an expected consequence of the different number of strokes in each shape. All remaining data were normally distributed except the data for *Matching of Two Lines*, where we applied Aligned Rank Transform (ART) [56] to normalize the data. The non-parametric data of the surveys met the preconditions for ANOVA; thus, we used ANOVA after applying ART to transform the data. Qualitative data from the questionnaires were analyzed using both non-parametric Kruskal-Wallis and Friedman’s tests. We did not observe any difference between both analysis approaches. Statistical results are shown in Table 2. For brevity, we only report significant results here; the remainder of the analysis, including the interactions between conditions, can be found in the supplementary materials.

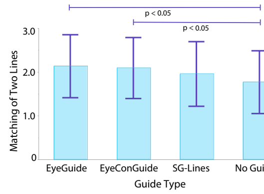
6.2.1 Visual Guides.

- *Task Completion Time*: No significant main or interaction effects were found for the techniques.
- *Shape Likeness* There was a significant main effect on *Shape Likeness* scores on visual guides (Figure 8(a)). A post-hoc analysis identified that participants drew better with *(i)* EyeGuide than SG-Line and No Guide, *(ii)* with EyeConGuide than No Guide, and *(iii)* SG-Line than No Guide (Figure 8(a)). Among all scored sketches (Figure 7), EyeConGuide was used for the highest-scored sketches for both shapes, while No Guide was used for the lowest-scored sketches for both shapes.
- *Stroke Quality:* Regarding *Line Straightness*, *Degree of Deviation*, *Corrective Movements*, and *Overall Score* (Figure 8(c) - Figure 8(f)), participants had better scores with all visual guides (EyeGuide, EyeConGuide, SG-Line) than with No Guide. For *Matching of Two Lines*, users matched lines better with EyeConGuide and EyeGuide than No Guide (Figure 8(b)).
- *User Experience Results* Regarding the SUS, EyeConGuide received an excellent ‘B’ grade (82.9±9.1), both EyeGuide (69.2±20.0) and SG-Line (67.7±14) received an okay ‘C’ grade, and No Guide received a ‘D’ grade (47.3±21.3). For the NASA TLX, there was no significant effect between visual guides and spatial abilities on the questions (See Supplementary Materials). In the case of user preferences, the participants significantly preferred EyeConGuide over SG-Line and No Guide. Furthermore, they preferred EyeGuide over SG-Line and No Guide (Figure 9). The feedback from the users supported the individual benefits of the techniques. The participants who preferred EyeConGuide commented that *“...it is easy to draw”*, *“...made the task easier and faster”*, and *“...made it easy to track guide and match lines”*. The participant who preferred EyeGuide commented that they *“...could check the model’s accuracy by just looking”*. The participant who preferred SG-Line commented it is *“...easy to see grids”*. Finally, the participant who preferred No Guide commented that *“Guides cannot make me focus on what the shapes look like while drawing”*.

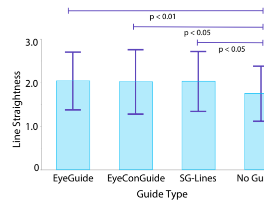
6.2.2 Spatial Ability. We further investigated how participants from different spatial ability groups performed with each guide type and how these performances differed from each other. We particularly focused on the evaluation metrics where we observed a statistical significance as the main effect of spatial ability, *Shape Likeness* and *Degree of Deviation*. Regarding *Shape Likeness*, we observed that HSA participants’ drawings received higher scores (by 2.1 pts out of 20) than LSA ones.



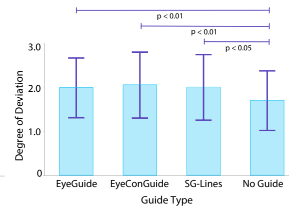
(a) Shape Likeness



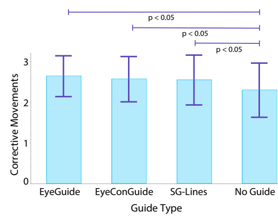
(b) Matching of Two Lines



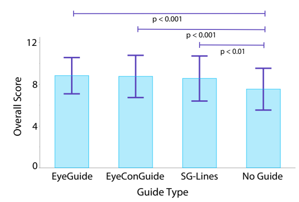
(c) Line Straightness



(d) Degree of Deviation



(e) Corrective Movements



(f) Overall Score

Figure 8: Study 2: Experimental results across all 6 measures for each technique. All plots show a post-hoc difference between guides, where EyeGuide, EyeConGuide, and SG-Line are better than No Guide. EyeGuide was better than SG-Line only for *Shape Likeness*. Error bars show the standard deviation of data. The dark blue lines represent the significant differences across the guide types when averaged across HSA and LSA participant groups.

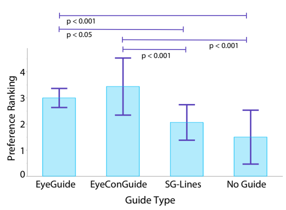


Figure 9: Average preference rankings across all the participants. Error bars show the standard deviation of data. The plot shows that EyeConGuide and EyeGuide were preferred over SG-Line and No Guide by our participants.

The post-hoc analysis shows that the HSA participants group scored statistically significantly higher than the LSA group for EyeGuide and No Guide. We performed further post-hoc analysis among guide types separately for HSA and LSA groups, as presented in Figure 10 (a, b). The HSA participants drew better with EyeConGuide, EyeGuide, and SG-Line than with No Guide. They also drew significantly better with EyeGuide than SG-Line. On the other hand, the LSA participants drew better only with EyeConGuide and EyeGuide than with No Guide, while we observed no statistically significant difference between SG-Line and No Guide or EyeGuide and SG-Line. Additionally, the highest-scored sketches came from the HSA participants, while the lowest-scored sketches came from the LSA ones (Figure 7). For example, for shape likeness, the top score was 10 from a HSA participant, and the lowest score was 1 from a LSA participant.

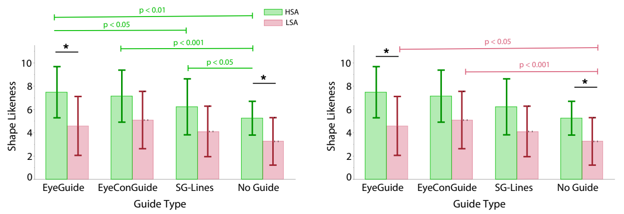
Regarding the *Degree of Deviation*, the post-hoc analysis shows that the HSA participants scored higher than the LSA participants in the EyeGuide, EyeConGuide, and No Guide. We performed further post-hoc analysis among guide types separately for HSA and LSA groups, as presented in Figure 10 (c, d). Both the HSA and LSA participants drew better with EyeConGuide, EyeGuide, and SG-Line than with No Guide.

6.3 Discussion

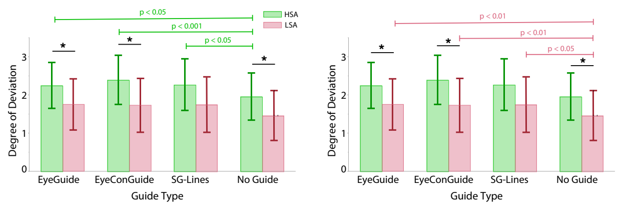
In the second user study, we evaluated the proposed gaze-based guides with complex 3D models. For RQ1, our results indicate that the proposed methods (EyeGuide and EyeConGuide) improve users' accuracy while sketching in terms of shape likeliness and *Stroke Quality*. Regarding *Shape Likeness*, we find EyeGuide and EyeConGuide to exhibit significantly higher scores than the SG-Line and No Guide. This shows that the use of eye-tracking in the design of visual guides can improve the user's sketching accuracy. It points to our initial thesis, that users could plan their hand movements more accurately if guidance is given at the visual attention area. Furthermore, our post-hoc analysis showed that participants drew better with EyeGuide and EyeConGuide than No Guide in all evaluated metrics. The results also indicate that the participants' *Shape Likeliness* and *Stroke Quality* (i.e., *Degree of Deviation*, *Corrective Movements*, and *Overall Score*) results were superior for SG-Line compared to No Guide. These results confirm prior findings that visual guides improve accuracy [5, 9].

We also note that, while no significance was observed between SG-Line and No Guide, both gaze-based methods offered an additional improvement over No Guide in terms of *matching two lines*. The evaluation metric tells us whether the user can connect two lines or not, which requires users to plan their hand movement to the position of a previously drawn stroke in space [6]. A reason for this result could be that gaze-based methods allow users to look where they want to draw and show a visual guide in the vicinity of that location, which helps them better plan their hand movement to existing points of the graphic.

Finally, we did not observe a significant difference between EyeConGuide, EyeGuide, and SG-Line concerning *Task Completion*



(a) Shape Likeness for High Spatial Ability (HSA) Participants
(b) Shape Likeness for Low Spatial Ability (LSA) Participants



(c) Degree of Deviation for High Spatial Ability (HSA) Participants
(d) Degree of Deviation for Low Spatial Ability (LSA) Participants

Figure 10: *Shape Likeness* and *Degree of Deviation* scores split for HSA and LSA participants. The red horizontal lines illustrate the significant differences for LSA participants, and the green horizontal lines illustrate the significant differences for HSA participants. Finally, the black bars illustrate the significant differences between HSA and LSA participants for each guide type. The plots show that HSA participants drew better with EyeConGuide, EyeGuide, and SG-Line than with No Guide, while LSA participants only drew better with EyeConGuide and EyeGuide than with No Guide. Error bars show the standard deviation of data.

Time or the other measures of *Stroke Quality*, which is in line with previous findings that gaze and controller input methods typically do not show significant performance differences [30, 42, 57]. Yet, the results showed that EyeGuide provides better *Shape Likeness* than SG-Line and that EyeGuide and EyeConGuide increase the ability of the users to matching two lines, highlighting that the proposed gaze-based guides improve the user performance for some aspects of 3D sketching.

Regarding RQ2, EyeConGuide received the highest grade for SUS and the user preference questionnaire compared to all of the analyzed techniques [46]. The scores of both gaze-based guides (i.e., EyeConGuide and EyeGuide) were also significantly higher than No Guide and SG-Line. These comments support our hypothesis that gaze-based guides provide a better experience, not only over No Guide but also SG-Line. This is further supported as 14 out of 16 participants found our guides to be useful tools for sketching in 3D, while the other two participants preferred No Guide because guides prevented them from focusing on what the shapes looked like. Visual guides can sometimes be perceived to be obstructive, and to assist the user during sketching, we had to show the visual guides within the scene so that they covered some visible space. These comments on guides interfering with participants’ focus on shapes might potentially explain no significant differences in NASA-TLX results for visual guides. They are also in line with the findings of Arora et al. [2], despite only two participants mentioning this. Both SG-Line and our gaze-based techniques offer guides that dynamically fade, which leads to a different experience than always-on guides or No Guide. The actual impact of guides’ dynamics on users’ level of distraction should be further studied in the future.

For RQ3, our results show a statistical difference between spatial ability groups and visual guides in *Shape Likeness* and *Degree of Deviation*; see Table 2. Regarding *Shape Likeness*, HSA participants performed significantly better than LSA participants while using EyeGuide and No Guide. Our results further illustrate that the LSA participants scored significantly better in terms of *Shape Likeness* while using EyeGuide and EyeConGuide than No Guide while no significance was observed between SG-Line and No Guide. Interestingly, HSA participants also scored significantly better while using SG-Line as well than No Guide and using EyeGuide than SG-Line. This shows that the use of eye-tracking in the design of visual guides can improve the user’s sketching accuracy, while the behavior of these improvements highly depends on the level of their spatial ability. We found that HSA participants scored higher than LSA participants in all scored categories. We also identified that HSA participants created the highest-scoring sketches, and LSA ones did the lowest-scoring sketches. This result matches previous work [5] within our context.

Similarly, the *Degree of Deviation* performed by the HSA participants was found to be significantly higher than the LSA participants while using EyeGuide, EyeConGuide, and No Guide. Unlike the *Shape Likeness* measure, we observed any type of grid lines to be statistically significantly better than No Guide — regardless of the SA participant group.

Our results highlight the importance of user-centered design approaches, where each individual might require a different system adaptation. By understanding the specific needs and preferences of individuals with HSA and LSA, designers can create more tailored and effective visual guides, ultimately improving the usability of 3D sketching systems and applications. Moreover, based on our results, people who teach 3D sketching should consider tailoring instructional strategies to each individual’s abilities to improve their skills.

7 INSIGHTS INTO GAZE-BASED GUIDES FOR 3D SKETCHING

This work investigates novel eye-tracking guides to support 3D sketching. We now discuss the findings of our research across both basic (Section 5) and complex (Section 6) task experiments. By analyzing both studies together, we can derive a clearer picture about the effect of the proposed techniques on the whole 3D sketching process, and not just on one of its parts.

Our main insight is that, in contrast to the state of the art, the *gaze-based guidance improves sketching accuracy and usability*, and as such, our work was successful in identifying the beneficial properties of the concept. While EyeGuide makes participants sketch with less deviation, for basic shapes EyeConGuide was the most preferred guide. For complex sketches, EyeGuide makes users sketch shapes more closely to the intended drawing than SG-Line does, without a significant penalty on *Task Completion Time*. Previous work on basic shapes found that adding visual guides increased drawing time [2]. However, we did not see similar results for either task, as there was no significant difference between visual guides. One possible reason for this is that for complex shapes, the time "saved" by not following the guide might be "added" to the time needed to plan their next stroke. We base this reasoning on previous work [6, 9] that identified hand positioning in space and planning the hand movement direction as distinct planning sub-actions for 3D sketching. In basic one-stroke shapes, users only need to focus on planning their hand movement. However, for complex multi-stroke shapes users need to take other strokes into account when planning their hand movement. Hence, it seems reasonable that adding a visual guide does not increase time, as it helps users identify the spatial relationship *between* strokes faster when planning the next stroke.

Moreover, an important aspect of gaze-based assistance is that the improved performance can come at a compromise of usability as the guides can only partially cover the user's intention through eye movement. Some participants noted that grid fragments could obscure the scene's visibility and affect the system usability, which corroborates previous work on visual guides in a VE [47]. Regardless, our participants preferred using EyeGuide and EyeConGuide over the other methods since the sketching performance was prioritized. Moreover, EyeConGuide is the only interaction technique that achieved a "B" on the SUS questionnaire.

Finally, when comparing the outcomes of two user studies, it becomes apparent that the proposed methods affect user performance and experience differently for basic and complex shapes. For example, for basic shapes, we found a statistically significant difference between EyeGuide and EyeConGuide regarding *Shape Deviation*, but we did not find such differences for complex shapes. These results show that it is important to consider the tradeoff between multimodal and unimodal interaction techniques [36], and that for basic shape sketching, unimodal interactions might be better.

7.1 Limitations

This paper evaluated our proposed interaction techniques in two user studies with 16 participants each. Similarly to previous work [8, 9], we averaged the metrics for all sketch types, reducing our data analysis's complexity. One limitation of our results is the sample size: we only had two participants per condition. Yet, when looking at the effect size of the statistically significant results (Table 1 and Table 2), we can see that all η^2 are over 0.14, which show a large effect size. Another limitation is that we changed the way to measure accuracy between Study 1 and Study 2, where we could not measure the *Shape Deviation* in Study 2 in the same manner. This was solely due to the challenges in implementing a standard *Shape Deviation* algorithm that can deal with the widely varying sketching results observed in the participants' drawings. Instead, we scored the *Shape Likeness* and *Stroke Quality* of the sketches manually in both studies, to enable us to compare results across studies.

Another limitation is the participants' demographics, e.g., handedness, gender, age, and drawing experience. In the future, we plan to further evaluate our user interface with a larger and more varied population. Finally, we only tested our proposed guides for 3D sketching in VR. In the future, we will test our gaze-based interaction techniques in other modalities, like 3D sketching with devices like the 3Doodler or a PHANToM.

8 CONCLUSION

In this paper, we proposed using gaze as a new modality to assist users in sketching better in 3D environments by presenting two novel eye-gaze-based guide mechanisms: EyeGuide and EyeConGuide. We conducted two user studies to evaluate the proposed techniques. In the first user study, participants sketched two basic shapes, while in the second study, participants sketched two complex shapes. The results identified that gaze-based guides (EyeGuide and EyeConGuide) improve line straightness, degree of deviation, and shape likeliness for simple and complex shapes. Moreover, EyeConGuide exhibited a higher usability score, and participants preferred gaze-based guides over controller-based visual guides and no guides. We also found that HSA participants drew more accurate shapes than LSA. Overall, our results identify that using eye-gaze assistive systems as visual guides can improve users' accuracy and the user's experience in 3D sketching as they make the systems more usable. We hope our results encourage practitioners, developers, and designers to embed eye-gaze-based visual guides into their sketching applications to improve the 3D sketching performance of users.

ACKNOWLEDGMENTS

This research was funded by TUBITAK 1002 - Short-Term Research and Development Funding Program, grant number 123M150. This research was also supported by the Pioneer Centre for AI, DNRF grant number P1.

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