Smart3DGuides: Making Unconstrained Immersive 3D Drawing More Accurate

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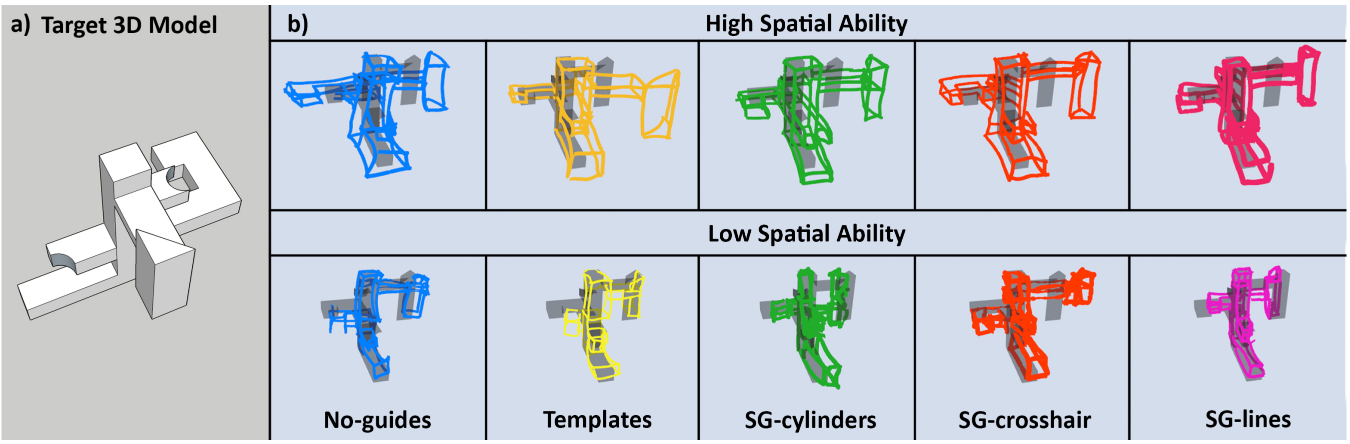

Figure 1: (a) Target 3D model, and (b) 3D drawings made without and with Smart3DGuides.

ABSTRACT

Most current commercial Virtual Reality (VR) drawing applications for creativity rely on freehand 3D drawing as their main interaction paradigm. However, the presence of the additional third dimension makes accurate freehand drawing challenging. Some systems address this problem by constraining or beautifying user strokes, which can be intrusive and can limit the expressivity of freehand drawing. In this paper, we evaluate the effectiveness of relying solely on visual guidance to increase overall drawing shape-likeness. We identified a set of common mistakes that users make while creating freehand strokes in VR and then designed a set of visual guides, the Smart3DGuides, which help users avoid these mistakes. We evaluated Smart3DGuides in two user studies, and our results show that non-constraining visual guides help users draw more accurately.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**.

KEYWORDS

Virtual Reality Drawing, 3D User Interfaces, Drawing

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1 INTRODUCTION

The recent availability of relatively inexpensive high-quality Virtual Reality (VR) headsets has made immersive 3D drawing tools available to artists and those in fields like architecture and industrial design. For these users, drawing objects directly in 3D is a powerful means of information exchange, avoiding the need to project the idea into a 2D sketch [Israel et al. 2009]. Especially for architecture and industrial design professionals, this allows them to sketch ideas without using the conventions used to represent 3D objects in 2D, which can require extensive training [Hennessey et al. 2017; Keshavabhotla et al. 2017]. Most current commercial tools, including Tilt Brush [Google 2016], GravitySketch [GravitySketch 2018] and Quill [Facebook 2018], let users directly draw 3D objects in a virtual environment (VE) using freehand drawing. This technique is intuitive, easy to learn and use for conceptualizing new shapes, which assists the creative process [Wesche and Seidel 2001]. Despite these claimed advantages, prior work shows that the resulting 3D sketches are less accurate than 2D ones [Arora et al. 2017; Wiese et al. 2010]. Various explanations for this difference have been proposed, including depth perception issues [Arora et al. 2017; Tramper and Gielen 2011], higher cognitive and sensorimotor demands [Wiese et al. 2010], and the absence of a physical surface [Arora et al. 2017].

Broadly speaking, the inaccuracies of 3D sketches fall into two independent categories: lack of shape-likeness and lack of stroke precision. A 2D analogy is helpful here. A drawing of a square lacks shape-likeness if the overall shape is not close to being square, no matter how straight the lines are or how precisely they meet at their ends. A drawing lacks stroke precision if the strokes are not reasonably straight or do not meet at their ends. While lacking shape-likeness is almost never desirable [Israel et al. 2009; McManus et al. 2010; Ullman et al. 1990], low stroke precision is often intentional since it can make a drawing more expressive [Cooper 2018]. Further, drawings that are excessively precise violate the principle that "preliminary ideas should look preliminary" [Do and Gross 1996; W. Buxton 2007]. This may affect the design process since users often focus on details instead of the overall design [Robertson and Radcliffe 2009]. Still, some limited assistance for stroke quality might be helpful, as it can be difficult to draw even straight lines [Arora et al. 2017; Wiese et al. 2010] and simple shapes [Barrera Machuca et al. 2019] in VR.

A good user interface should help the user achieve an appropriate and intended stroke quality for the drawing. Various methods have tried to address this inaccuracy; see related work. However, many require mode-switching or other interaction techniques, which can be intrusive and take the user out of the freehand drawing experience. They also often fail to distinguish between lack of shape-likeness and lack of stroke precision, making it impossible to create drawings that have high shape-likeness while still containing loose, expressive strokes. In 2D, visual non-constraining guides enable likeness while still allowing expressivity. They help users draw accurately but do not snap, straighten or re-position the strokes in any way. Figure 2 shows a drawing made with Adobe Photoshop Sketch [Adobe 2018], using non-constraining visual perspective guides. These guides let the artist achieve accurate perspective, analogous to high shape-likeness, while allowing loose, expressive strokes.

Figure 2: Adobe Photoshop Sketch drawing with high shape-likeness and intentionally loose stroke quality. ***By Ian Eksner.***

Visual guides in 2D are typically in a separate layer behind the user's drawing. The direct 3D analog would be a lattice in space, but this would be far too intrusive and distracting. Perspective makes it dense in the distance, and close parts would appear between the user and the drawing, blocking the view and shifting distractingly as the user's head position changes.

In this paper, we present Smart3DGuides, a set of visual guides that help users improve the shape-likeness and stroke precision of VR freehand sketching without eliminating the expressiveness of their hand movements. Our interface design implicitly helps users to identify potential mistakes during the planning phase of drawing [Jin and Chusilp 2006], so they can proactively fix these errors before starting a stroke. Our work extends beyond the physical actions, defined by Suwa et al.'s design-thinking framework [Suwa et al. 1998] as those that create strokes, to better describe the process of planning a stroke. Previous work has shown that this technique provides good insights into the cognitive process [Coley et al. 2007; Kavakli et al. 2006]. We identified three necessary sub-actions when planning a stroke in VR: choosing a good viewpoint and view direction in 3D space, positioning the hand to start the stroke in space as intended in all three dimensions, and planning the hand movement to realize the correct stroke direction and length. To achieve our goal, Smart3DGuides automatically shows visual guidance inside the VE to help users avoid mistakes during these three planning sub-actions. This visual guidance is based on the current user view direction, controller pose, and previously drawn strokes, and provides users with additional depth cues and orientation indicators.

We are explicitly not aiming to replace 3D CAD software, which is appropriate for late stages of the design process. Instead, we see Smart3DGuides as a way to make freehand VR drawing more useful during the *conceptual stage* of the design process [Lim 2003], when sketches help the designer develop thoughts and insights, and that are used to transmit ideas [Keshavabhotla et al. 2017]. Previous work has found that VR drawing during the conceptual stage adds to the design experience and enhances creativity [Rieuf and Bouchard 2017]. Our contributions are:

- **Identifying sub-actions for planning a stroke in VR:** We identify three user planning sub-actions: choosing the viewpoint, the initial hand position, and the movement direction.
- **Smart3DGuides:** An automatically-generated visual guidance inside the VE that uses the current user view direction, controller pose and previously drawn strokes. Smart3DGuides help users realize potential planned actions and address common drawing errors.
- **Smart3DGuides Evaluation:** We evaluate the accuracy of Smart3DGuides in a user study that compares them with freehand 3D drawing and with visual templates. Our results show that non-constraining visual guides can improve the shape-likeness and stroke quality of a drawing. We also did a usability study of Smart3DGuides, in which participants found our visual guides useful and easy to use.

2 RELATED WORK

Sketching is an iterative process with different phases [Jin and Chusilp 2006], including *planning*, when the user plans a new stroke and *creation*, when the user draws the stroke. To create better user interfaces, it is important to understand the different challenges users face in each phase, both in 2D and 3D.

2.1 User Errors During Drawing

Previous work has studied the cause of user errors during 2D drawing. For example, Ostrofsky et al. [Ostrofsky et al. 2015] studied the effect of perception on drawing errors. They identified that perceptual and drawing biases are positively correlated. In other words, an inaccurate perception of the object being drawn causes drawing errors. Chamberlain and Wagemans [Chamberlain and Wagemans 2016] studied the differences between misperception of the object and drawing in more depth. They conclude that delusions, i.e., errors in the conception of the image, have more impact on the success of drawing than illusions, i.e., errors in the perception of an image. They also found that individual differences in visual attention reliably predict drawing ability but did not find a strong effect of user motor skills. We did not find any work that identifies the reasons behind drawing errors in VR.

2.2 Challenges for 3D Drawing in VR

During the planning phase, users face challenges related to depth perception and spatial ability. Arora et al. [Arora et al. 2017] identified that depth perception problems affect 3D drawing. These problems are a known issue with stereo displays, in particular distance under-estimation [Renner et al. 2013] and different targeting accuracy between movements in lateral and depth directions [Barrera Machuca and Stuerzlinger 2019; Batmaz et al. 2019]. They contribute to incorrect 3D positioning of strokes, as the user needs to consider spatial relationships while drawing [Bae et al. 2009]. Sketching requires individuals to use all elements of their spatial ability [Branoff and Dobelis 2013; Orde 1997; Samsudin et al. 2016] and their spatial memory of the scene [Shelton and McNamara 1997]. Previous work found a relationship between the user's spatial ability and their 3D drawing ability [Barrera Machuca et al. 2019], their 2D drawing ability [Orde 1997; Samsudin et al. 2016], and their ability to create 3D content [Branoff and Dobelis 2013].

During the creation phase, users face challenges related to eye-hand coordination. For example, Wiese et al. [Wiese et al. 2010] found that 3D drawing requires higher manual effort and imposes higher cognitive and sensorimotor demands than 2D drawing. This higher effort is a consequence of the need to control more degrees of freedom during movement (3/6DOF instead of 2DOF). Tramper and Gielen [Tramper and Gielen 2011] identified differences between the dynamics of visuomotor control for lateral and depth movements, which also affects eye-hand coordination. Arora et al. [Arora et al. 2017] found that the lack of a physical surface affects accuracy since users can only rely on eye-hand coordination to control stroke position.

2.3 3D Drawing Tools

Early systems like 3DM [Butterworth et al. 1992], HoloSketch [Deering 1996] and CavePainting [Keefe et al. 2001] demonstrated the potential of a straight one-to-one mapping of body movements to strokes for 3D drawing. This technique, called freehand 3D drawing, is easy to learn and use [Wesche and Seidel 2001]. With it, users create strokes inside the VE by drawing them with a single hand. Yet, the unique challenges of 3D drawing in VR reduce the accuracy of user 3D strokes compared to 2D ones with pen and paper [Arora et al. 2017; Wiese et al. 2010]. Previous work explored different user interfaces for accurate drawing in a 3D VE. Some approaches use novel metaphors to constrain stroke creation [Bae et al. 2009; Dudley et al. 2018; Jackson and Keefe 2016], while others beautify the user input into more accurate representations [Barrera Machuca et al. 2018; Fiorentino et al. 2003; Shankar and Rai 2017]. A third class of approaches helps avoid depth perception issues by drawing on physical or virtual surfaces, e.g., on planes [Arora et al. 2018; Barrera Machuca et al. 2018; Grossman et al. 2002; Kim et al. 2018] or non-planar surfaces [Google 2016; Wacker et al. 2018]. However, work on creativity has found that users limit their creativity based on a system's features and that constraining user actions can have negative effects [Lim 2003; Pache et al. 2001].

Another approach is to use various types of guides. Some 3D CAD systems use widgets to constrain user actions, like snapping points [Barrera Machuca et al. 2018; Bier 1990], linear perspective guides [Bae et al. 2009; Kim et al. 2018], and shadows that users can interact with [Kenneth et al. 1992]. Others use visual templates [Jackson and Keefe 2004; Wacker et al. 2018; Yue et al. 2017], which are static 2D or 3D guides that the user can trace after positioning in the VE. Other types of templates are 2D or 3D grids that provide global visual feedback [Arora et al. 2017; Israel et al. 2013]. A final approach uses orientation indicators in 3D CAD systems [Fitzmaurice et al. 2008; Khan et al. 2008] to help users identify local and global rotations.

In contrast to previous work, our Smart3DGuides interface does not constrain user actions and does not use templates. Our guides are visually minimal but support creating complex shapes since our interface automatically adapts to the previously drawn content, the current viewpoint and direction, and the user's hand pose in space. Our Smart3DGuides also focus on helping users improve their shape-likeness and stroke expressiveness over precision.

3 IMMERSIVE 3D SKETCHING STROKE PLANNING SUB-ACTIONS

This work aims to reduce the potential for errors in VR drawing. The lack of previous work on the causes of such mistakes made our first goal be understanding user actions in VR sketching when planning a stroke. We tackle this by dividing them into sub-actions, an approach that has been shown to help understand complex cognitive processes [Suwa et al. 1998]. We believe that helping users avoid mistakes in these sub-actions will result in better sketches. On the other hand, a mistake done in one planning sub-action can affect the others. We focus on three planning sub-actions, all affected by the challenges of 3D drawing. We hypothesize that they are crucial to drawing accurately in VR and call these sub-actions *VR stroke-planning actions*:

(a) **Orientating the viewpoint relative to the content:** This planning sub-action helps users position their view to draw a precise stroke. It requires users to correctly identify the objects shapes and the spatial relationship between objects [Baker Cave and Kosslyn 1993]. Correct identification of a 3D shape is view-dependent [Tarr et al. 1998; Zhao et al. 2007], especially if the user is focusing on another task [Thoma and Davidoff 2007]. For 3D sketching, Barrera et al. [Barrera Machuca et al. 2019] identified that the way users move around their drawings affects the shape-likeness of the sketch. Based on this, we assume that a good viewpoint is one that lets the user correctly identify the previous strokes' actual shape so they can plan the next stroke. For example, accurately identifying a previous stroke's direction is needed to draw a new stroke that is parallel to it. To measure this sub-action, we assume that the deviation between the real stroke and the perfect one quantifies the error in viewpoint orientation: if users do not position their viewpoint correctly, they may not be able to see the stroke deviating from the intended position. This is an extension of Schmidt et al.'s [Schmidt et al. 2009] work, in which they identified that for 3D curve creation in 2D, the drawing viewpoint affects accuracy. We expect that strokes made from a good viewpoint will have smaller deviations than those made from a bad viewpoint.

(b) **Hand positioning:** This planning sub-action helps to accurately position a stroke in space. It is needed to match strokes to previous content, which is required for high-quality sketches [Wiese et al. 2010]. This planning sub-action needs users to correctly perceive their hand position in space, and can be affected by depth perception issues of stereo displays [Barrera Machuca and Stuerzlinger 2019; Batmaz et al. 2019] and the lack of a physical surface [Arora et al. 2017]. Both Arora et al.'s [Arora et al. 2017] and Barrera et al.'s [Barrera Machuca et al. 2019] work identify depth as a variable that affects the stroke precision and shape-likeness. Thus, we assume that the distance from the start vertex to the closest adjacent previous stroke quantifies errors in hand positioning. We expect that fewer errors in the hand positioning sub-action will result in smaller distances between strokes.

(c) **Planning the hand movement direction:** This planning sub-action needs users to plan their hand movement in the correct direction to avoid corrective movements and drawing axis changes [Wiese et al. 2010]. It poses high demands on distance perception [Kenyon and Ellis 2014; Renner et al. 2013] and spatial abilities [Branoff and Dobelis 2013; La Femina et al. 2009; Orde 1997]. Following Arora et al. [Arora et al. 2017] and Wise et al. [Wiese et al. 2010], we assume that the amount of corrective movement at the end of a stroke quantifies this planning sub-action. We expect that fewer errors in the movement direction will result in smaller corrective movements.

Based on the above-mentioned work on 2D drawing errors and the challenges of 3D drawing, we hypothesize **(H1)** that helping users avoid errors in VR stroke-planning actions increases the stroke precision and shape-likeness of the drawing. We expect that being able to visualize the effect of their VR stroke-planning actions improves drawing accuracy compared to no visualization. A possible confound is the combination of several mistakes while creating a stroke, which is amplified by the lack of a physical surface [Arora et al. 2017] and issues with eye-hand coordination [Wiese et al. 2010]. However, if a user correctly plans a stroke, such errors should affect the final sketch less.

4 STUDY 1: IMMERSIVE 3D SKETCHING STROKE PLANNING SUB-ACTIONS

The objective of this study was to verify that we can identify VR stroke-planning actions, and to inform the design of our visual guides. Thus, we recreated real-world sketching conditions, letting participants follow their own sketching strategies, even though we limited the drawn shape. This approach lets us observe the participant's drawing process but makes it more difficult to use quantitative methods for sketch scoring. Prior 3D sketching evaluations [Arora et al. 2017; Dudley et al. 2018; Wacker et al. 2018] were controlled studies in which the participants had to follow a pattern, start a stroke in a specific position, do single strokes, or a combination of all these strategies. Using their scoring methods in our scenario would require non-trivial algorithms, like 3D corner detection and shape matching for 3D objects that consist of irregular hand-made strokes. Thus, we used a mixture of qualitative and quantitative methods to score participant sketches.

4.1 Methodology

4.1.1 Participants: We recruited ten participants from the local university community (4 female). Two were between 18-20 years old, three 21-24 years, four 25-30 years, and one was over 31 years old. Only one participant was left-handed.

4.1.2 Apparatus: We used a Windows 3.6 GHz PC with an Nvidia GTX1080 Ti, with an HTC Vive Gen 1, a TPCast wireless transmitter, and two HTC Vive controllers. We provided participants with a 4 m diameter circular walking area free of obstacles (Figure 3a). The 3D scene was displayed in Unity3D and consisted of an open space with no spatial reference except for a ground plane (Figure 3b). Users used their dominant hand to draw the strokes with a freehand drawing technique and their non-dominant hand to specify the start and end of each trial. To reduce potential confounds, the drawing system provided only basic stroke creation features and did not support features like stroke color, width, or deletion. We displayed an image of the current target object in front of the participant (Figure 3b). This image disappeared while participants were drawing a stroke to avoid simple tracing movements, which are different from drawing movements [Gowen and Miall 2006].

4.1.3 Shapes: We used three shapes (Figure 3c), two similar to Shepard and Metzler mental rotation objects [Shepard and Metzler 1971], and one with curved segments, since curves are integral to the design process [Schmidt et al. 2009]. Choosing geometric shapes with moderate complexity allowed all participants to finish the shape regardless of their spatial ability or 3D sketching experience.

4.1.4 Procedure: Participants answered a questionnaire about their demographics. Then the researcher instructed participants on the task. Participants were encouraged to walk and move around while drawing. We told participants to draw only the outline of the model and to keep the drawing's size similar to the reference object, but did not limit our participants in any way once they started drawing. We also told them that we were not evaluating their drawing ability or their ability to recall an object, but that they should try to draw the object as accurately as possible without adding extra features. Finally, after receiving these general instructions, participants were trained on how to use the system.

At the beginning of each trial and before putting on the VR headset, participants saw 2D renderings on paper of the 3D model they were going to draw. They could ask questions about the camera position for each view. Once participants felt comfortable with the object, they walked to the starting position inside the circle

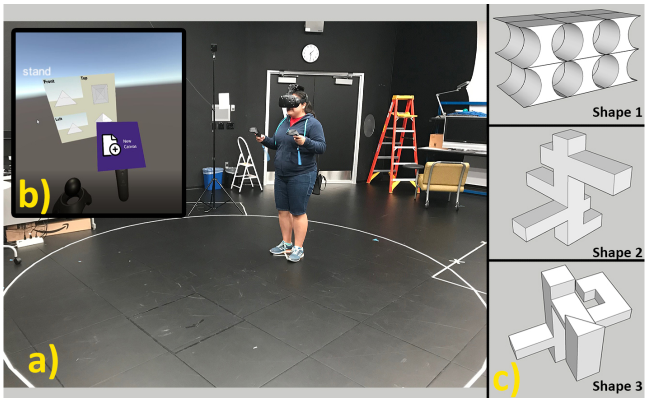

Figure 3: (a) Experimental setup, (b) the user's view and (C) 3D models the participants attempted to draw.

(Figure 3a) and put the VR headset on. Then they pressed the non-dominant hand touchpad to start the trial and were asked to press that touchpad again when they finished their trial drawing. Each trial lasted a maximum of ten minutes. Between trials, participants rested as long as they needed, but at least 2 minutes. Each participant did three drawings in total.

4.2 Scoring

An author with artistic training scored each drawing in a VE, comparing the user's strokes to the 3D model. The scorer could rotate the sketch to identify errors. We standardized the sketches' sizes by uniformly scaling them to the same height. We also rotated the drawings to match the top two corners of the model.

For **stroke quality** we use Wiese et al.'s [Wiese et al. 2010] coding method, which evaluates each stroke in four categories: line straightness, whether lines connect, how much two lines on the same plane deviate, and corrective movements at the end of the line. The evaluator considered each category individually and scored each between 0 (very poor) and 3 (very good) for the whole drawing, summing to 12 points in total which represents the total stroke quality.

Shape likeness 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. For shape likeness, the scorer rated each drawing separately, giving a score between 1 and 10 using the 3D model as a reference. They then compared all drawings of the same participant, and compared each drawing to drawings with similar scores, standardizing scores across participants. Similar approaches to qualitative scoring have been used before [Chamberlain et al. 2011; McManus et al. 2011; Tchalenko 2009].

4.3 Results

After scoring the sketches, the average scores from the ten participants were the following: line precision = 7.5 pts (max 12 pts) and shape likeness = 7.4 pts (max 10 pts). The standard deviations were 1.02 pts and 0.91 pts respectively. Based on their average shape-likeness score, we selected the best (line precision = 8.97 pts and shape likeness = 8.67 pts) and worst participant (line precision = 6.75 pts and shape likeness = 6.01 pts). Figure 4 shows their sketches.

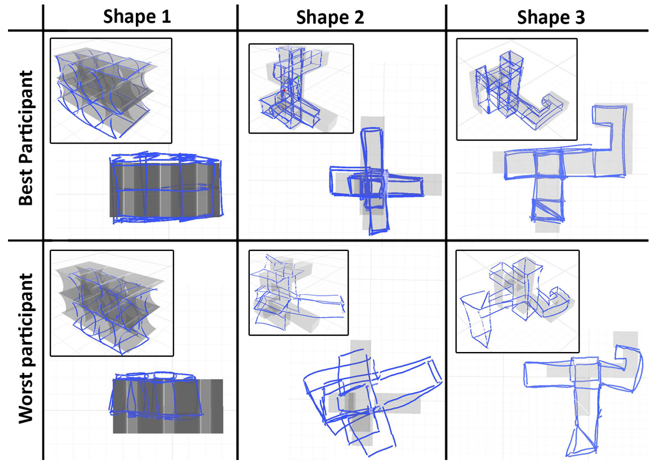

Figure 4: Drawings by the best and worst participants.

4.4 Discussion

Our goal was to test whether VR stroke-planning actions are present and to see if the challenges of VR sketching cause users to make more errors. As there is no previous work that discusses the causes of errors while drawing in VR, we selected the two participants with the most complementary results to make it easier to identify how errors in VR stroke-planning actions affect the final sketch. Because we cannot know the user's intention for drawing a stroke, we looked only at orthogonal stroke pairs. This approach gave us a reference frame for the user's intention. Although we evaluated each VR stroke-planning actions separately, we expect that the errors of one sub-action affect the others.

For each selected sketch, six in total, we extracted pairs of lines and analyzed them to calculate user errors. Each pair consisted of one existing line and one line that started near an endpoint of that line and that was approximately perpendicular to it. For simplicity we excluded lines that were not approximately straight, including the curved lines from Shape 1 and cases where the user drew multiple edges with a single connected stroke. We also excluded lines that had been traced over previous ones, since tracing is different from drawing [Gowen and Miall 2006], and lines that were not approximately axis-aligned like the diagonal lines in Shape 3, since one of our measures is based on projecting lines to their most parallel axis.

For each pair of lines, we call the previously-drawn line PQ and the new line GH (Figure 5). The high-score participant had 108 orthogonal pairs, and the low-score participant 113. We used the shapes' corners to identify the participant's intent for the new stroke and compared it to the actual one to calculate the error for each planning sub-action.

(a) **Orienting the viewpoint relative to the content** (Figure 5b): To find errors in viewpoint orientation, we first project PQ onto its parallel axis to construct a new segment P_1Q_1 and construct a plane GH_1 that goes through G and is perpendicular to P_1Q_1. We then compute the distance from H to the plane GH_1. For the high-score participant this distance

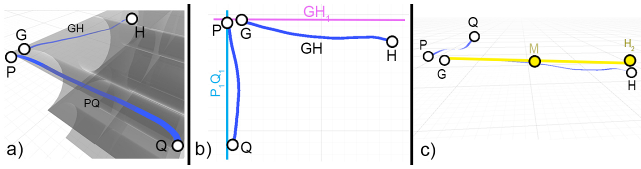

Figure 5: VR stroke-planning actions calculations. The blue lines are a selected pair *PQ* and *GH*. (a) Perspective View, (b) top view, and (c) front view.

was on average 12% smaller than for the low-score one (300 vs 340 mm). This distance represents the viewpoint error, because the selected viewpoint did not allow the participant to see that *GH* was not perpendicular to *PQ*.

(b) **Hand positioning** (Figure 5a): To find errors in hand positioning, we calculated the distance between the new line's start point *G* and the existing line's endpoint *P*. We found that for the high-score participant the distance was on average 33% smaller than for the low-score participant (20 vs 30 mm). This distance represents the hand-positioning error, because the position of *G* does not match *P*.

(c) **Planning the hand movement direction** (Figure 5c): We calculated the amount of correction by computing the distance between the real end vertex *H* and the point H_2 where the stroke would have ended had it continued in the original direction. For the original direction we used the start vertex *G* and a point *M* halfway along the stroke. The line length, the start vertex, and the stroke direction give a probable ending point H_2. For the high-score participant this distance was on average 33% smaller than for the low-score one (60 vs 90 mm). This distance represents the planning-direction error, because the position of *H*2 does not match *H*.

In conclusion, we identified that when users make more VR-action errors, their shape-likeness and stroke precision scores diminish. These results support our **H1** and verify that Coley et al.'s [Coley et al. 2007] work on dividing complex actions into sub-actions helps to identify users' errors. Our results also informed the design of the Smart3DGuides introduced below. Limitations of our VR stroke-planning actions analysis include being based on a controller instead of a pen, since different tools have differences in accuracy [Batmaz 2018], and not considering hand jitter, which has an effect on virtual hand pointing [Carignan et al. 2009]. We believe that these limitations do not affect the underlying depth perception and spatial orientation issues, which are the principal cause of VR-action errors. Other methods to model performance using hand and head data, e.g., Fitts' Law [Fitts and Peterson 1964], are outside of our scope.

5 SMART3DGUIDES

We propose *Smart3DGuides*, a set of visual guides inside the VE that help novice users draw more accurately without sacrificing stroke expressiveness. They are purely visual and non-constraining — our goal is to help the user position and move the controller more accurately, but to have the resulting strokes track the controller position without straightening, snapping, or other modification. This gives users the full freedom of freehand 3D drawing while reducing its cognitive load and error-proneness. We avoided creating an interface that actively guided the user, which could be counterproductive because we wanted our users to focus on sketching and not on the capabilities of the system. Our visual guides help users draw shapes without guessing their intention, which would be required for beautification [Barrera Machuca et al. 2018; Fiorentino et al. 2003; Shankar and Rai 2017] or with templates [Arora et al. 2017; Yue et al. 2017]. Based on previous results on automatic visual guides [Yue et al. 2017], we hypothesize **(H2)** that *using Smart3DGuides increases the stroke precision and shape-likeness of the drawing*. We expect that with Smart3DGuides people will draw more accurately than with no guides or with manually positioned templates.

We designed Smart3DGuides to help avoid the errors in VR stroke-planning actions demonstrated in Study 1. The design was also informed by guidelines for 3D sketching interfaces by Barrera et al. [Barrera Machuca et al. 2019], which suggest that a good user interface should reduce the effect of depth perception errors and lessen the cognitive and visuomotor demands of drawing in 3D. It should also help users understand the spatial relationships between the strokes so that they can draw more accurate shapes. Study 1 showed that these challenges directly affect VR stroke-planning actions, which in turn affect the final sketch. Thus, a user interface that helps users identify errors during VR stroke-planning actions should increase drawing accuracy.

We designed and evaluated three different kinds of guides:

(a) **SG-crosshair** uses the controller position and orientation as a reference frame.
(b) **SG-lines** uses a fixed global reference frame that is independent of the content and controller.
(c) **SG-cylinders** uses the existing content as a reference frame.

We believe these effectively span the space of visual guide design. All provide visual guidance in the important areas of viewpoint orientation, depth, and movement guidance, but they provide them in different ways. Table 1 summarizes the differences and Section 5.1 provides full details on each one.

Table 1: Smart3DGuides summary

Visual Guide	*Fixed Ref. Frame*	*Local Ref. Frame*	*Position*
SG-crosshair	Stroke coordinate system, created using the first drawn stroke direction	Controller pose	Controller position
SG-lines	Global coordinate system	N/A	Fixed in space, within 30 cm of the controller
SG-cylinders	Stroke coordinate system, created using the first drawn stroke direction	Controller pose and previous stroke direction	*Outside stroke:* controller position *Inside stroke:* closest stroke vertex

5.1 Visual Guides

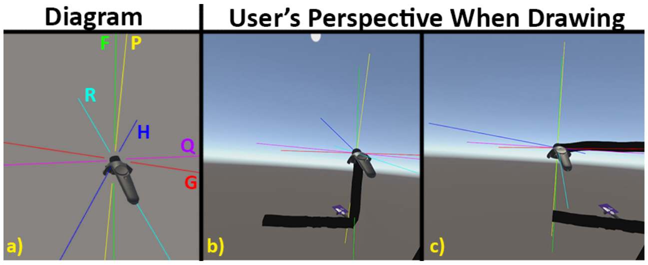

Figure 6: SG-crosshair always follows the controller orientation and position.

5.1.1 SG-crosshair. (Figure 6). This guide gives the user a reference frame based on the controller orientation. It consists of two 3-axis crosshairs drawn in different colors that follow the controller position. The first crosshair, RPQ in Figure 6, is oriented using the controller local reference frame, shifting as the user changes the controller's orientation. The second, HFG, follows the world reference frame. If the user's first stroke was approximately horizontal, the axes of the world reference frame are the world up vector, the direction of the user's first stroke, and their cross product. If the user's first stroke was not approximately horizontal, we instead use the vector pointing directly away from the user. We use lines as visual guidance to better represent the crosshair as an extension of the controller that does not react to the strokes. With this guide we tried to simulate using a ruler to draw a stroke; after orienting the RPQ crosshair a user can follow it with the controller.

The deviation between the two crosshairs helps users understand the controller orientation relative to the world and the content. SG-crosshair provides viewpoint guidance by letting users match their position and orientation to the world reference frame. It provides depth guidance by letting users see where the crosshairs intersect existing content. Movement guidance comes from setting the controller orientation relative to the world reference frame and then following one of the crosshair axes.

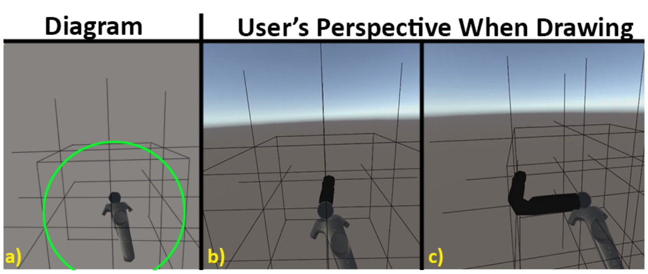

Figure 7: SG-lines stays static regardless of the controller and stroke orientation.

5.1.2 SG-lines. (Figure 7). This guide creates a global 3D lattice and displays part of it depending on the controller position. It is completely static and does not move or change its orientation. The 2D-drawing analogy is a grid. The lattice consists of cubes 20 cm on a side and we show cube edges that have an endpoint within 30 cm of the controller. We do not render lines if they are too close to the user to avoid having lines point directly at the users' face, and the distance limit prevents displaying an infinite lattice, which would be visually too dense. SG-lines provides viewpoint guidance by letting users match their position and orientation to the lattice lines. It provides depth guidance by letting users see when the controller intersects the lattice. Movement guidance comes from following lattice lines.

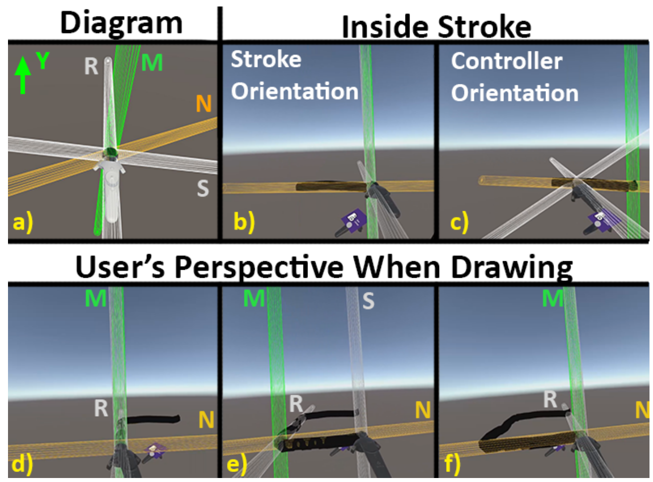

Figure 8: (a) SG-cylinders when the controller is outside a stroke. (b)-(c) When the controller is inside the stroke, the RS cylinder orientation depends on the controller orientation, being either completely perpendicular to the stroke (b) or following the controller orientation (c). (d)-(f): when the user is drawing, the MN cylinder position stays static until the drawn stroke is the same length as the previous stroke. The MN cylinder orientation matches the previous stroke.

5.1.3 SG-cylinders. (Figure 8). This guide gives users a reference frame that evolves with the shape they are sketching. With SG-cylinders we tried to simulate rotating the canvas to better correspond to the drawn shape, because the visual guide matches the previous content and users can use it to draw the new strokes. To emphasize the connection of the reference frame with the drawn strokes that our system renders as cylindrical tubes, SG-cylinders uses cylinders for visual guidance.

The SG-cylinders algorithm has two steps. First, we set the fixed reference frame (FRF) for the session. This FRF consists of the global up vector, the direction of the user's first stroke, and the cross product between both vectors. If the user's first stroke was vertical, the system uses the vector pointing directly away from the user to create the cross product. In the second step, SG-cylinders uses this FRF, the current controller orientation, the previous strokes orientation, and the current viewpoint orientation to update the visual guides. SG-cylinders consists of two pairs of crossed cylinders drawn in different colors. These cylinders' position depends on whether the user is drawing or not, and their orientation depends on the controller distance to an existing stroke.

The first cylinder pair is MN, which helps users plan the orientation of their viewpoint relative to drawn strokes. MN let users see how their viewpoint is rotated based on the FRF. MN functionality is as follows: When the user is ***not drawing*** the MN intersection point follows the controller position. For orientation, when the controller is *outside* a stroke, the M cylinder points towards the global up vector, helping to position content parallel to the walking plane. The N cylinder is parallel to the horizontal axis most perpendicular to the view direction of the FRF. If the view direction is between two axes, N is rotated 45° to show the user that they are viewing the shape from a diagonal view. When the controller is *inside* a stroke, N matches that stroke's orientation to create a local reference frame (LRF) (Fig. 8b-c). Once the user ***starts drawing***, MN remains fixed at the position the user started the stroke, and with the orientation it had. However, if the new stroke began *inside* a previous stroke, MN changes its position when the new stroke approaches the same length as the previous stroke. The new position shows users where the new stroke needs to end to have the same length (Fig. 8e-f).

The second crossed cylinder pair is SR, which helps users plan their hand movement direction. it also help users position their hand in space, allowing them to see their hand position relative to distant content. When the user is ***not drawing*** SR follows the controller position. For orientation, when the controller position is *outside* a stroke, the R cylinder follows the controller's forward direction. The S cylinder is perpendicular, following the controller's roll. When the controller is *inside* a stroke, R's orientation is perpendicular to the stroke direction. And S's orientation is the same as the stroke direction (Fig. 8b) if the controller rotation is within 15° of being perpendicular to the stroke direction. If it is larger than 15°, it changes to the controller rotation (Fig. 8c). When the user ***starts a stroke*** *inside* another stroke, the RS cylinders' position and orientation complement the MN cylinders, so users have multiple references inside the VE. R's position is the starting position inside the previous stroke, and its orientation is perpendicular to N. S's position matches the controller position, and its orientation matches M's orientation (Fig. 8e).

SG-cylinders provides viewpoint guidance by letting users match their position and orientation to the MN cylinders. It provides depth guidance by letting users see when the controller is inside a stroke using the RS cylinders and the M cylinder. Movement guidance comes from following the cylinders.

5.2 Implementation

We implemented this system in Unity/C# on the same system used in study 1. For the VR headset, we again used an HTC Vive with two HTC Vive controllers and a TPCast wireless transmitter. Our system only supports one Smart3DGuide at a given time, which prevents mode errors.

6 USER STUDY 2: SMART3DGUIDES EVALUATION

The objective of this study was to see whether guides that are only visual and do not embed knowledge of the object being drawn can help users increase their stroke precision and shape-likeness. We measure accuracy through shape-likeness, how similar a drawn shape is to the target one, and stroke quality, how similar each drawn stroke is to an intended one.

We evaluated our new guides by comparing the quality of 3D sketches done with Smart3DGuides, with freehand 3D drawing, and with visual templates. We choose to compare our interface to freehand drawing to let users focus on the underlying strokes without the distractions provided by the addition of visual guides. We also evaluated non-constraining visual templates, since we believe them to be the most-used visual guidance most similar to Smart3DGuides. Such templates can be found in Tilt Brush [Google 2016] and other programs. Users can manually place them inside the VE and then trace over them; usual shapes are planes, cubes, cylinders and spheres. We also compared the performance of the three Smart3DGuides since each is based on a different reference frame.

6.0.1 Participants: we recruited twelve new participants from the university community, none of which had been part of User Study 1. Five were female. One participant was between 18-20 years old, six 21-24 years, four 25-30 years, and one was over 31 years old. Only one participant was left-handed. The participants' frequency of drawing with pen and paper was that one drew every day, two a few times a week, five a few times a month, two once a month, and two less than once a month. For 3D modelling, three modelled a few times a week, one about once a week, and eight less than once a month. For drawing in VR, eight participants had never drawn in VR before, two a single time, and two between 2-4 times.

6.0.2 Apparatus, Procedure, Scoring: First, we evaluated the spatial abilities of each participant through the VZ-2 Paper folding test [Ekstrom et al. 1976] and Kozhevniko's spatial orientation test [Kozhevnikov and Hegarty 2001]. Based on the participant's scores in both tests, we used results from previous work [Barrera Machuca et al. 2019; Lages and Bowman 2018] to separate our participants into two groups, low spatial ability (LSA) and high spatial ability (HSA). Through screening in the initial study phase, we ensured that we had equal numbers of participants with high and low spatial ability. Hardware setup and experimental procedure were identical to study 1, but each participant drew a single shape five times. Each session lasted 40 to 60 minutes, including the time for the spatial ability tests. The software was updated to show the Smart3DGuides. Users again used their dominant hand to draw the strokes with the freehand drawing technique. We used the same qualitative scoring method for the final sketches as in study 1. To avoid confounds, the scorer did not know the participant's spatial ability or the sketch condition.

6.0.3 Shape: Participants drew only a single shape (Figure 1a), which was selected through a pilot study that adjusted task difficulty. We deliberately choose a shape with moderate complexity, as it needed to be non-trivial for HSA participants but not too frustrating for LSA ones. We also wanted to ensure that participants were drawing the shape they were seeing and not relying on previous knowledge about a given object.

6.1 Design

The study used a 5x2 mixed design. The within-subjects independent variable was the type of visual guide (none, templates, SG-lines, SG-crosshair, SG-cylinders) and the between-subjects independent variable was the user's spatial ability (low vs high). In total, we collected 60 drawings, 5 for each participant. Because both ability groups had the same number of participants, our design was balanced between factors. The order of conditions across within-subject dimensions was counter-balanced across participants. The collected measures were drawing time, total time, the stroke geometry in Unity3D, and the participant's head and hand position. We also recorded the participants and their views while drawing.

6.2 Results

Results were analyzed using repeated measures ANOVA with $\alpha = 0.05$. All the data were normally distributed, except for drawing time, match line, and shape-likeness. To normalize that data, we used the aligned rank transform ART [Wobbrock et al. 2011] before ANOVA. Statistical results are shown in Table 2. Figure 1 shows the target object and exemplary resulting 3D drawings.

Table 2: User study 2 statistical results. Green cells show statistically significant results

	Spatial Ability (SA)		Visual Guide (VG)		VG x SA	
Measure	$F(1,9)$	p	$F(4,39)$	p	$F(4,39)$	p
Total Time	2.88	0.79	5.7	0.04	0.36	0.8
Drawing Time	2.32	0.16	11.19	<0.001	2.5	0.05
Line Straightness	16.6	0.002	3.16	0.02	0.78	0.53
Matching of Line Pairs	1.09	0.32	3.69	0.01	0.29	0.87
Degree of Deviation	2.22	0.17	18.16	<0.001	0.14	0.96
Corrective movements	1.6	0.23	7.59	0.00013	0.56	0.69
Shape Likeness	25.34	0.0007	4.64	0.003	0.97	0.43

6.2.1 Total Time & Drawing Time: There was a significant main effect of visual guide on total time. Overall, users were faster in the no-guides conditions than in all other ones. Cohen's d=0.50 identifies a medium effect size. There was also a significant main effect of visual guides on drawing time. Overall the no-guides condition was faster than the three Smart3DGuides conditions, and the templates condition was faster than the SG-cylinders condition. Cohen's d=0.33 identifies a small effect size.

6.2.2 Stroke quality: We scored each drawing using the same method as study 1. There was a significant main effect of spatial ability on **line straightness**. Overall the HSA participants achieved better line straightness scores than LSA participants. There was a significant main effect of visual guides on the stroke quality. A post-hoc analysis for technique showed that for line straightness ($F_{4,39} = 3.16, p < 0.05$) participants drew straighter lines with SG-lines than with the templates ($p < 0.01$). Cohen's d=0.47 identifies a small effect size. There was no interaction between spatial ability groups and visual guides. For the **matching line** criterion ($F_{4,39} = 3.68, p < 0.01$) participants matched the lines better with the SG-lines condition than with no-guides ($p < 0.05$) and templates ($p < 0.01$), and with the SG-cylinders conditions than with the templates ($p < 0.05$). Cohen's d=0.28 identifies a small effect size. For the **degree of stroke deviation** ($F_{4,39} = 18.16, p < 0.0001$) and **corrective movements** ($F_{4,39} = 7.59, p < 0.0001$) the SG-lines and SG-cylinders conditions were better than no-guides, the templates and the SG-crosshair. Cohen's d=1.16 identifies a large effect size for degree of stroke deviation. Cohen's d=0.49 identifies a small effect size for corrective movements. Finally, when considering total stroke quality, our results identify a significant difference between visual guides ($F_{4,39} = 4.64, p < 0.01$). Cohen's d=0.36 identifies a small effect size. The post-hoc analysis of the results shows that SG-lines is 24% better than no-guides ($p < 0.0001$), 26% better than templates ($p < 0.001$) and 16% better than SG-crosshair ($p < 0.01$). SG-cylinders is 19% better than no-guides ($p < 0.01$) and 20% better than templates ($p < 0.001$). Overall, SG-lines and SG-cylinders increased user stroke precision.

6.2.3 Shape-likeness: We scored each drawing using the same method as in study 1. There was a significant main effect on shape-likeness scores between LSA and HSA participants ($F_{1,9} = 25.34, p < 0.01$). Overall, HSA had higher scores than LSA. There was also a significant main effect on visual guide ($F_{4,39} = 4.64, p < 0.01$), but no interaction between spatial ability and visual guides. A post-hoc analysis shows that SG-lines are 9% better than no-guides ($p < 0.05$). SG-cylinders and SG-crosshair were not statistically significantly different from no-guides. Cohen's d=0.81 identifies a large effect size.

6.2.4 Qualitative Questionnaire: Eight participants preferred drawing with SG-lines, three with SG-cylinders and one with SG-crosshair. For shape accuracy, eight participants felt that SG-lines made them the most accurate, two SG-cylinders, one SG-crosshair, and one the templates. However, for line precision, eight participants selected SG-lines and four SG-cylinders.

6.3 Discussion

Our first goal was to identify if our proposed Smart3DGuides, which are only visual, increase user shape-likeness and stroke precision while drawing in VR.

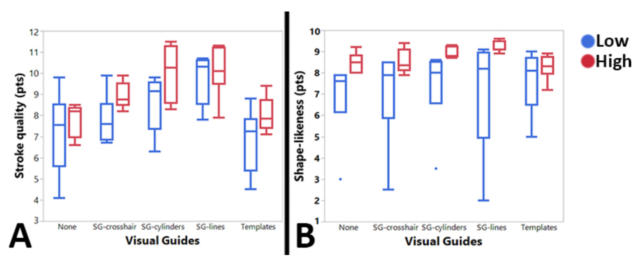

Figure 9: Study 2 results, a) stroke quality, and b) shape likeness

For *stroke-quality* (Fig. 9a), our results show that visual guides help users improve their stroke precision without compromising expressiveness by constraining their actions. These results confirm **H1**, as helping users avoid errors in the VR stroke-planning actions creates better drawings. They also strengthen the case for using VR drawing for the conceptual design stage [56]. One important finding is the effect of the guide visual presentation on stroke precision. SG-crosshair and SG-cylinders have similar functionalities, but different visual presentations, and our results show that SG-cylinders improved stroke precision, but SG-crosshair did not. This effect does not seem to affect SG-lines, but it uses a different reference frame. This shows that selecting the correct presentation is an important part of the design of 3D immersive drawing tools.

For *shape-likeness* (Fig. 9b), we tested three reference frames, controller-based, global, and content-based. Our results show that the global reference frame improves shape-likeness. We also confirm previous results on the relationship between total score and spatial ability [Barrera Machuca et al. 2019]. Further, there was no interaction between spatial ability and guide, which shows that Smart3DGuides helped both classes of users. This shows that our new guides are universally beneficial. Note that for HSA participants the lowest scores for SG-lines are better than the highest scores with no guide, even for shape-likeness, which already had a high baseline. This result supports **H2**, as SG-lines improved both the shape-likeness of the drawing and the stroke precision without affecting stroke expressiveness. Without knowledge of what the user is drawing, other previously proposed user interfaces for VR drawing cannot support all three goals simultaneously. Based on this we recommend adopting SG-lines in VR drawing systems.

In conclusion, for shapes that are mostly axis-aligned, a simple form of visual guidance, like provided by SG-lines, helps users improve both the stroke quality and shape-likeness of 3D sketches.

7 USER STUDY 3: USABILITY EVALUATION

Study 2 was a formal evaluation of Smart3DGuides in a constrained laboratory setting, where the participants drew pre-selected geometrical shapes. In contrast, we designed study 3 to test Smart3DGuides in a situation more similar to a real-world sketching scenario. Based on the success of highly evolved commercial 2D drawing systems that use non-constraining guides, e.g., Adobe Sketch [Adobe 2018], we hypothesized (**H3**) that our guides will not hinder the sketching process and that designers will find them useful.

7.0.1 Participants: We recruited ten novice users to evaluate the usability of the Smart3DGuides (6 females). One was between 18-20 years old, one 21-24 years, six 25-30 years, one 31-35, and one over 35. All participants were right-handed. The participants' frequency of drawing with pen and paper was that four drew a few times a week, one a few times a month, and five less than once a month. For 3D modelling, one modelled a few times a week, two a few times a month, and seven less than once a month. All participants had drawn in VR fewer than five times, and for six it was the first time.

7.0.2 Apparatus: The hardware setup was identical to the above studies, but we added the ability to change stroke colour and size, and to delete strokes to the 3D sketching system. These changes allowed us to have a system with similar stroke creation features as commercial 3D sketching systems.

7.0.3 Procedure: The experimental procedure was identical to the above studies. The only difference was that participants had 5 minutes each to draw one shape repeatedly. Between each sketch, the participants answered System Usability Scale (SUS) [Brooke 1996] and Perceived Usefulness and Ease of Use (PUEU) [Davis 1989] questionnaires. They were also given questions about how they used the visual guides and what they liked and disliked about them. At the end of the study, the participants answered a questionnaire regarding their whole experience. Each session lasted 40 to 60 minutes, including the time for filling the questionnaires.

7.0.4 Shape: The drawn shape (Figure 10a) included arcs, straight lines, curves, and parallel or perpendicular lines, similar to the elements found in the design task for a new object. As the complexity of the shape might be high for novices, we told participants to focus more on the process of drawing and less on finishing the shape.

7.1 Design

The within-subjects independent variable was the type of visual guide (none, SG-lines, SG-cylinders, SG-crosshair). In total, we collected 40 drawings, 4 for each participant. The order of Smart3DGuides conditions for the within-subject dimension was counterbalanced across participants, but all participants drew the none condition first to establish a reference for the usability of the visual guides. The collected measures were the stroke geometry and the participant's head and hand positions. We also recorded the participants and their views while drawing.

7.2 Results

Table 3: User study 3 questionnaires results

	SG-Lines	*SG-Cylinders*	*SG-Crosshair*
SUS	75.0	58.8	61.5
PUEU	3.9	3.5	3.4

7.2.1 SUS questionnaire: We scored the SUS questionnaire results following its guidelines. According to previous work [Bangor et al. 2008], a user interface with a score over 68 can be considered good. The SG-lines condition had a passing score, but SG-Crosshair and SG-Cylinder did not (Table 3).

7.2.2 PUEU questionnaire: According to previous work [Brinkman et al. 2009], for a 5-points scale, if a user interface has a score over 3.7 in a component-based usability questionnaire it can be considered good. The SG-lines condition has a passing score, but SG-Crosshair and SG-cylinders did not (Table 3).

7.2.3 Smart3DGuides comparison: Four participants preferred SG-crosshair, four SG-lines, one SG-cylinder and one preferred having no guides. When asked about shape accuracy seven participants said that using SG-lines made them most accurate, one SG-cylinders, one SG-crosshair and one no guides. For line precision, seven participants said that using SG-lines made them more precise and all other conditions got one vote.

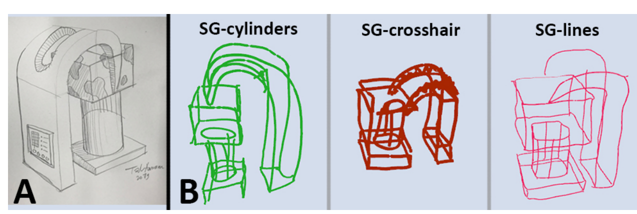

Figure 10: (a) Study 3 drawn shape, and (b) participants' sketches

7.3 Discussion

Our goal was to identify whether novice users found our proposed Smart3DGuides useful and easy to use in a real-world drawing task. Based on both the SUS and PUEU questionnaire results, we can conclude that novice users found SG-Lines useful. The written answers from our participants further complement these results. For example, P4 stated about SG-Lines, *"[they are] intuitive and easy to understand"*, and P10 said, *"the lines gave me more confidence and support to make shapes be straighter"*. The results from study 3 complement those from study 2, as SG-lines not only helped achieve better accuracy but are also easy to learn and use.

The participants were also asked about how they used Smart3D-guides. Their responses illustrate their use during the stroke planning phase. For SG-cylinders, P1 said *"I tried to align the smart guide with what I was drawing,"* and P2 said, *"I used the white cylinder as a way [to] know where my stroke would end and correct the movement accordingly."* For SG-lines, P2 said *"I used the grid as a way to use units [each block in the grid was a unit] and that's how I kept an informal record of the proportions among the geometric shapes,"* and P3 said *"[I used it] to locate some key points."* Finally, for SG-crosshair, P4 said *"I would align the relative and the fixed lines before I start[ed] drawing a line,"* and P6 said *"using the purple line to help to orient the different parts of my drawing within space and the other lines to orient the lines of the drawing with one another."* These results show that the design of the Smart3DGuides was successful, and that participants used them to avoid errors in VR stroke-planning actions.

Users reported problems with the visual aspect of SG-cylinders; P4 said *"the cylinders felt big and visually intrusive."* Others had trouble with the amount of information displayed for SG-crosshair; P5 said *"it was difficult to keep track of all of them [lines]."* These problems made users find these guides challenging to use. For SG-cylinders P10 said *"I did not understand how to use it. I think if I understood it better, I would be able to use this method better"* and for SG-crosshair P2 said *"it was hard to know what each line represented, especially since some of them are dynamic and changed according to where my hand was."* These results show the importance of limiting the information provided to novice users while drawing as well as considering the visual aspect of the guides.

8 CONCLUSION

In this paper, we presented Smart3DGuides, a set of non-constraining visual guides for 3D sketching that help users avoid errors. Based on our newly identified VR stroke-planning actions, we found that our new Smart3D-Guides SG-lines substantially improve over currently used guide technologies in 3D drawing systems. No previous work had considered such non-constraining guides. Their simplicity makes them easy to use for novice users and easy to adopt technically. Despite the simple nature of Smart3DGuides and in contrast to previous work [Bae et al. 2009; Dudley et al. 2018; Jackson and Keefe 2016], they improved the user's line precision and shape accuracy/likeness, regardless of their spatial ability. Our approach also helps users choose the appropriate stroke expressiveness for their task. In the future, we plan to work on new measures to quantify user errors while drawing in VR and to explore other combinations of visual guides.

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