# The Effect of Spatial Ability on Immersive 3D Drawing

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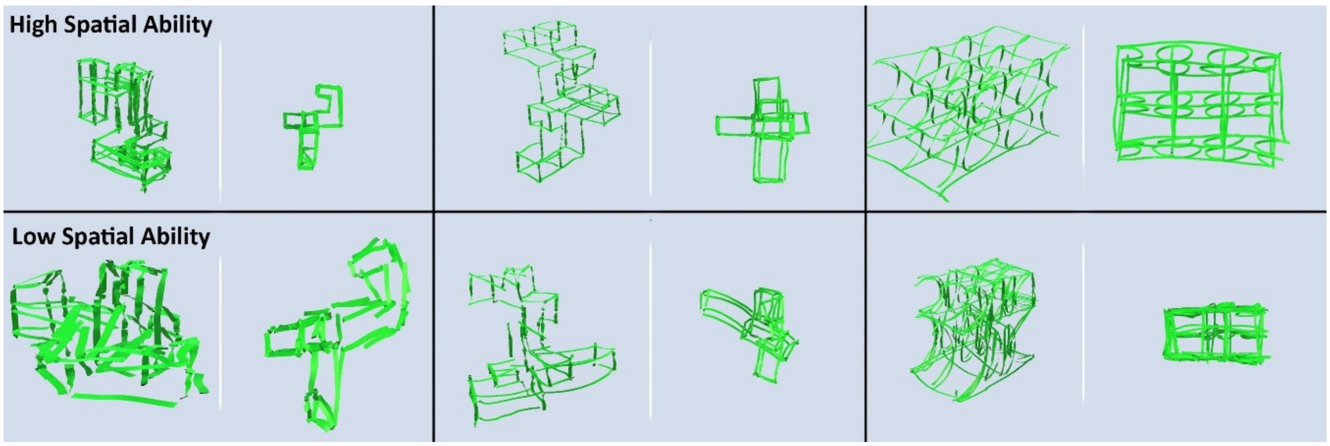


**Figure 1. 3D drawings made by high and low spatial ability participants while walking in study 1.**

**ABSTRACT**
Virtual Reality (VR) headsets have made immersive 3D drawing available to the general public. However, compared to 2D drawing, the presence of an additional dimension makes sketching in VR challenging, since creating precise strokes that are positioned as intended in all three dimensions imposes higher demands on the users' perception, motor and spatial skills. Another challenge users face is creating accurate shapes in which strokes are positioned correctly relative to previous ones, as they may need to use different views to plan their next hand movement. In this paper, we analyze the behaviours of users with different spatial abilities while drawing in VR. Our results indicate that there are different types of behaviours that affect different aspects of the sketches. We also found that the user's spatial ability affects the shape of the drawing, but not the line precision. Finally, we give recommendations for designing 3D drawing interfaces.

**Author Keywords**
Virtual Reality; 3D Sketching; Spatial Cognition.


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**CSS Concepts**
• Human-centered computing ~ Virtual reality • Human-centered computing ~ User studies

## INTRODUCTION

Drawing is an important element of human expression since it is an efficient way to convey information and to start the design process [54]. Recently, with the availability of affordable, high-quality Virtual Reality (VR) devices like the HTC Vive [25] and Oculus Rift [38], there has been a boom in the development of commercial tools for immersive 3D drawing, including Tilt Brush [20] and Quill [16]. These tools let users directly draw 3D objects in a virtual environment (VE) using freehand drawing. Users can also freely walk around their creations to see them from different perspectives. These two features have been touted as an advantage of 3D drawing tools for VR over other 3D object creation tools, as both, freehand drawing and walking are intuitive and easy to learn and use [55, 56]. Despite these claimed advantages, prior work shows that the resulting drawings are less accurate than 2D sketches [2, 57]. There are various possible explanations for this difference, including, but not limited to, depth perception errors [2, 53], higher cognitive and sensorimotor demands [57], and the absence of a physical surface [2]. One problem with this lack of accuracy is that it hurts the creative process since the sketch may not match the user intention.

This paper investigates users' behaviours during the stroke planning phase [28] while drawing in VR dependent on their spatial ability. Previous work has already shown that spatial ability influences 3D modelling in CAD programs [9, 14] and on 2D drawings [39]. However, no other work has studied the effect of the user's spatial ability on 3D immersive drawing and how it affects the final sketch. Through understanding users' behaviours during the stroke planning phase, our work extends previous work that analyzes the stroke creation process [2, 57]. In our first study, we investigate how participants create 3D sketches using freehand drawing while standing or walking. We found that the shape likeness of the drawing is affected by the user's spatial ability, but not the line precision, with sketches drawn by high-spatial-ability participants being more like the target shapes than sketches drawn by low-spatial-ability participants (Figure 1). We found no difference between standing and walking, but when only consider walking the high-spatial-ability user's movement was more systematic than the low-spatial-ability user's movement. This difference affects their shape likeness. In our second experiment, we further investigate the effect of viewpoint change on the stroke planning phase. We found that, when walking, the participant's shape likeness and line precision was better than when using hand-based view control. We also found that choosing the correct viewpoint to draw had a positive effect on the final sketch.

## RELATED WORK

### Challenges of 3D Drawing

3D stroke creation using VR devices is less accurate than 2D stroke creation using pen and paper [2, 57]. For example, Wiese et al. [57] found a difference in line precision and completion time between 2D and 3D sketches. They found that 3D drawing requires higher manual effort and imposes higher cognitive and sensorimotor demands than 2D drawing. This is a consequence of the need to control more degrees of freedom during movement (6DOF instead of 2DOF). Arora et al. [2] also found that users' shape likeness for VR decreased by 148%, using the metric of overall mean deviation from a target stroke. One possible explanation for this difference is the lack of a physical surface, since it forces users to rely only on their eye-hand coordination to control the stroke position. However, previous work by Tramper and Gielen [53] on eye-hand coordination has found a difference in the dynamics of visuomotor control for version and vergence. In this context, we understand version as coupled eye movements in the same lateral/vertical direction, and vergence as independent eye movements in opposite directions for depth accommodation. Arora et al. [2] also identify the depth perception problems associated with stereo displays as a likely reason for the inaccuracy of 3D immersive drawing. Such problems include the under-estimation of distances [42] and the targeting accuracy differences between movements in the vergence and the version direction [6, 7].

Another factor affecting 3D drawing is the correct positioning of a stroke in the 3D scene, as the user needs to consider the spatial relationships between objects while drawing [4]. This task relies on the user's spatial ability [9, 17], which consists of three elements: a) spatial visualization, the mental ability to manipulate 2D and 3D figures, b) spatial orientation, the ability to rotate mental representations of 2D and 3D objects, and c) spatial perception, the ability to be aware of one's relationship with the environment. A person's spatial ability is dependent on many factors, such as training [14, 46]. Previous work has found that individuals utilize all elements of their spatial ability [9, 39, 46] and their spatial memory of the scene [47] while drawing. For example, Orde [39] found that people with more developed spatial skills are more capable of converting an abstract mental picture into a concrete product and that the higher their spatial skills are, the more sophisticated their representation is. Samsudin et al. [46] also found that users with high spatial orientation can better conceptualize the world around them and thus can better solve orthographic drawing tasks. For 3D content creation, Branoff and Dobelis [9] found a relationship between the students' spatial abilities and their final scores in a university modelling course, and showed that students with high spatial ability got better scores on their 3D modelling test than low spatial ability students.

### 3D Drawing Tools

Creating a user interface that lets users accurately draw in a 3D virtual environment has been an open area of research for decades. Earlier systems such as HoloSketch [13] or CavePainting [29], showed the possibilities of directly drawing in 3D by using a straight one-to-one mapping of body movements to strokes. This technique, called freehand drawing, is easy to learn and use [56] and is the basis of most current commercial systems like FreeDrawer [56], Quill [16] and Tilt Brush [20]. However, the accuracy of freehand drawing is reduced by the stroke creation challenges presented above. Previously proposed user interfaces for immersive 3D drawing have tried to increase the user's line precision during the stroke creation process. Some tools like Lift-Off [27] and Drawing on Air [30] use novel metaphors to constrain the stroke creation process by reducing the demands on the user's visuomotor skills. Other tools reduce the user manual effort by beautifying strokes, i.e. Fiorentino et al. [18] and Multiplanes [5]. Beautification is the process of transforming informal and ambiguous freehand input to more formal and structured representations [37]. There are also tools that let users draw on a plane to reduce the effect of depth perception errors in stereo display systems. These include Digital Tape Drawing [22], ImmersiveFiberMesh [40], Multiplanes [5], and SymbiosisSketch [3].

Immersive 3D drawing tools also let users easily change their viewpoint [3, 5, 16, 20] by walking around their drawing. This characteristic is important since viewing a 3D object from multiple viewpoints helps users create a mental model of the object they are drawing [45, 50]. Some tools let users employ the *grab the air* interaction technique [44], or a variation of it, to further manipulate their drawings. For example, ImmersiveFiberMesh [40] and Digital Tape Drawing [22] use two-hand pan and zoom interaction, in which hand movement direction specifies the camera movement. Lift-Off [27] lets users grab the drawing with their non-dominant hand and reorient it by moving that hand. Previous work has studied the effect of changing the viewpoint on 3D CADs and found that it may lead to disorientation and frustration and suggested the use of widgets to help users [19, 32]. However no previous work has studied this effect on 3D immersive drawing.

## MOTIVATION

In this paper, we aim to identify the user behaviours during the stroke-planning phase while drawing in VR depending on their spatial ability. We focus on the stroke-planning phase since in this stage users mentally plan the next stroke based on the current drawing [28], choosing the viewpoint and the hand position from where to draw the new stroke. When selecting the viewpoint, the user shape likeness may be affected by the disorientation caused by low spatial updating [43, 52], which is the ability to create and update a mental model of the environment. This problem can be enhanced by the method used to control the view [8, 55]. When choosing the correct hand position, the user shape likeness and line precision may be affected by their depth perception [31], which depends on the display type [6, 7], and each individuals' vision system [24]. We also aim to quantify the effect of the user's spatial ability on their final 3D drawings. Understanding the effect of the spatial ability is important because planning the next stroke relies on the understanding of the correct relationships between the elements inside the 3D virtual environment, which heavily depends on the user's spatial ability [11].

Previously proposed user interfaces for 3D immersive drawing have focused on helping users create precise lines by solving the challenges of the stroke creation process. However, few tools have focused on solving the challenges of the stroke-planning phase, which is less understood. Helping users plan their next stroke is important: Israel et al. [26] showed that users expect that directly drawing in an immersive 3D environment will improve their spatial thinking, specifically improving their ability to draw 3D objects that have proper proportions relative to the user's bodies. Our final goal is to identify opportunities to develop better user interfaces for immersive 3D drawing based on the behavioural differences between spatial ability groups.

### Effect of spatial ability on immersive 3D drawing.

No previous work analyzes how the user's spatial abilities affect immersive 3D drawing. However, based on previous results on 2D drawing [39] and 3D modelling [9, 14], we hypothesize (***H1***) that *a user's spatial ability affects the shape likeness of the final drawing*. We expect that users with higher spatial abilities will draw shapes that are more similar to the example than those with lower abilities.

### Effect of viewpoint change while 3D drawing.

Previous work has found that when comparing walking and standing while doing a data analysis task [35], users' spatial abilities influence their performance. Similar to 3D drawing, data analysis is also a visually-demanding 3D task [35]. Based on this, we hypothesize (***H2***) that *a user's line precision and shape likeness diminish when they change their viewpoint while drawing*. We expect that when drawing while standing the user's line precision and shape likeness will be higher than when they walk while drawing.

### Effect of the user's behavioural differences based upon their spatial ability.

Two important elements of spatial ability are spatial orientation and spatial visualization, both of which are distinct abilities and affect the way the user understands the 3D environment [23, 34, 41]. Based on this relationship we hypothesize (***H3***) that *a user's spatial ability affects drawing behaviours in 3D regarding their hand position in space, viewpoint orientation and hand movement direction*. We expect that high-spatial-ability users draw differently than low-spatial-ability users.

## USER STUDY 1

This study aims to establish a baseline for freehand 3D immersive drawing depending on the user's spatial ability. It also evaluates the differences between staying in the same position and walking while drawing a single 3D object in VR.

### Methodology

#### *Participants*

We recruited 12 participants from the university community (7 female). 10 of participants were between 18-24 years old and 2 between 25-34 years old. Only one participant was left handed. The participants' frequency of drawing with pen and paper was, 1 drawing every day, 5 a few times a week, 1 once a week, 4 a few times a month, and 1 once a month. For drawing in VR, 8 of our participants had never drawn in VR before, 2 had drawn 2-4 times, and 2 had drawn between 5-9 times.

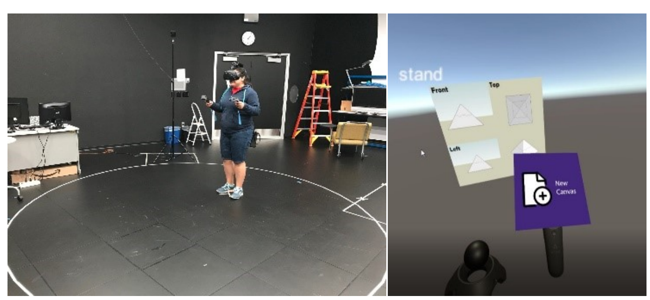


**Figure 2. a) Physical experimental setup with walking area. b) 3D environment of the experiment**

*Apparatus*

We used a 3.60 GHz PC with Windows and a NVidia GTX1080 Ti to run the experiment. We used an HTC Vive Gen 1 with a TPCast wireless transmitter and two standard HTC Vive Controllers. In the condition that allowed participants to walk, they were provided with a circular walking area with 4 m diameter free of any obstacles (Figure 2a). The 3D scene was displayed in Unity3D and consisted of open space with no spatial references (Figure 2b). Users used their dominant hand to draw the strokes and their non-dominant hand to specify the start and end of each trial. The drawing system provided only basic stroke creation features, with no additional features like colour, stroke width, or stroke deletion, to avoid distracting users. In the top left corner of the headset display, a message reminded users whether they should stand or walk around while drawing. In front of the participant, there was an image with the current object to draw. This image disappeared while participants were drawing a stroke to avoid tracing movements, which are different from drawing movements [21].

*Procedure*

First, participants were asked to complete two cognitive tests to measure their spatial ability: the vz-2 paper folding test [15] and the perspective taking / spatial orientation test [34]. Based on the participant's scores in both tests, we used previous work in the area [35] to separate our participants into two groups, low-spatial-ability (LSA) and high-spatial-ability (HSA). Participants then answered a questionnaire about their demographics. Subsequently, the researcher instructed participants in the task and explained and demonstrated which movements were allowed in the walking and standing conditions. In the standing condition, participants were not permitted to move their feet to physically move to a different place. The walking condition had no restrictions on movement and participants were encouraged to walk and move around while drawing. We also instructed participants to draw only the outline of the model and to keep the drawing's size similar to the reference object. We told participants 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 the general instructions, participants were trained on how to use the system.

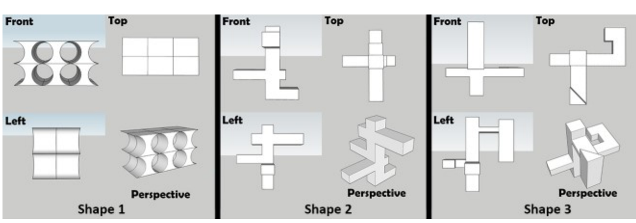


**Figure 3. Target shapes to be drawn by participants.**

At the beginning of each trial, participants saw 2D renderings of the 3D model they were going to draw on a sheet of paper. The views were from the front, top, side, and in perspective (Figure 3). During this phase, participants could ask questions about the camera position for each view. Once participants felt comfortable with the object, they walked to the marked position inside the circle (Figure 2a) and put the headset on. Then they pressed the non-dominant hand touchpad to start the trial and pressed that touchpad again when they finished their drawing. Each participant had a maximum of ten minutes to finish a trial. Between each drawing, participants rested for two minutes. Each participant did seven drawings in total, one for training and six for the study. Of the three shapes used, two were similar to the objects used in a Shepard and Metzler mental rotation test [48], and one had curved segments since curves are integral for the design process [2]. We chose geometrical shapes based on their complexity and to ensure that participants were drawing the shape they were seeing and not relying on previous knowledge about a given object. In addition, using geometric shapes allowed easier measurement and error quantification. After finishing all the drawings, the participants answered a questionnaire about their experience. Each session lasted between 40-60 minutes, including the time for the spatial ability tests.

**Design**

The study used a 2x3x2 mixed design. The within-subjects independent variables were movement type (walking vs. standing) and shape (1, 2, and 3). The between-subjects independent variable was spatial ability (low vs. high). In total, we collected 72 drawings, 6 for each participant. There were the same number of participants in both ability groups, so our design was balanced between factors. The order of conditions for both within-subject dimensions was counter-balanced across participants using a Latin-Square design. The collected measures were drawing time, total time, images of the 3D drawings, the stroke objects created in Unity3D, and the participant's head and hand position at every point in time. We also recorded video of the participants and created screen videos of the participants' views while drawing.

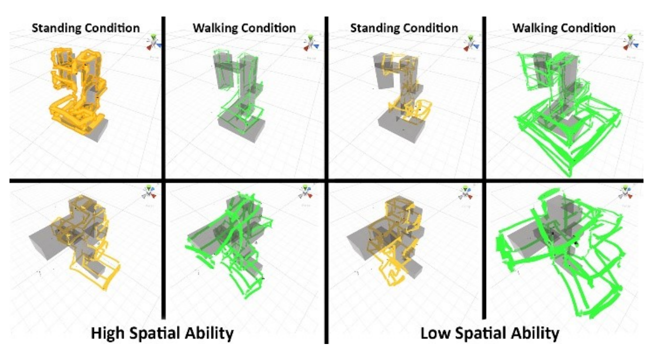


**Figure 4. Drawings done by participants.**

## Results

After collecting the drawings, we investigated several characteristics of the drawings and the drawing process to see how they were distributed, what their effect was, whether there was a correlation with spatial ability, and how they interacted. The measures were: total and drawing time, line precision, and shape likeness. We also analyzed the video capture and screen recordings to identify the different 3D drawing behaviours and verified that all the participants followed our instructions for the walking and standing conditions.

The results were analyzed using repeated measures ANOVA with $\alpha=0.05$. As the data for *line straightness*, *match line*, *corrective movement*, and *total time* was not normally distributed, we used an Aligned Rank Transform (ART) [58] before the ANOVA. All the other data was normally distributed. Statistical results are reported in Table 1, where "***" marks results with $p < 0.001$, "**" for $p < 0.01$, "*" for $p < 0.05$, "M.S." for marginally significant, and "N.S." for not significant.

| | SPATIAL ABILITY | | MOVEMENT | | MOVEMENT × SPATIAL ABILITY | |
|---|---|---|---|---|---|---|
| *MEASURE* | *F (1, 10)* | *p* | *F(1, 10)* | *p* | *F (1, 10)* | *p* |
| TOTAL TIME | 0.08 | N.S. | 53.2 | *** | 3.78 | M.S. |
| DRAWING TIME | 0.03 | N.S. | 6.3 | * | 0.35 | N.S. |
| LINE STRAIGHTNESS | 0.4 | N.S. | 29.3 | *** | 0.06 | N.S. |
| MATCHING OF LINE PAIRS | 1.68 | N.S. | 0.2 | N.S. | 0.26 | N.S. |
| DEGREE OF DEVIATION | 2.41 | N.S. | 0.14 | N.S. | 0.02 | N.S. |
| CORRECTIVE MOVEMENTS | 1.9 | N.S. | 1.12 | N.S. | 0.31 | N.S. |
| SHAPE LIKENESS | 13.5 | ** | 0.07 | N.S. | 0.15 | N.S. |

**Table 1. User study 1 statistical results. Green color shows significant difference.**

*Total Time:* Total time is the time participants spent drawing, which includes creating strokes, walking, and planning the next stroke. There was a significant main effect of movement type on total time ($F_{1, 10} = 53.2$, $p = 0.0001$). Cohen's $d = 0.6$ identifies a large effect size. Overall, participants spent a significantly longer time drawing in the walking condition than in the standing condition (Figure 5.1). There was no significant main effect between spatial ability groups for total time.

*Drawing Time:* Drawing time is the time participants spent creating strokes. There was a significant main effect of movement type on drawing time ($F_{1, 10} = 6.3$, $p = 0.03$). Cohen's $d = 0.35$ identifies a medium effect size. Drawing times for the walking condition were significantly longer than for the standing condition (Figure 5.2). There was no significant main effect between spatial ability groups for drawing time.

*Line precision:* We coded each drawing using the method from Wiese et al. [57] to evaluate the quality of the strokes. This coding method uses four categories: *line straightness*, *matching of line pairs, degree of deviation*, and *corrective movements*. Drawings were given a score between 3 (very good) and 0 (very poor). The sum of all the scores is called line precision. There was a significant main effect of movement type on line straightness ($F_{1, 10} = 29.3$, $p = 0.0003$), but not of spatial ability. Cohen's $d = 0.76$ identifies a large effect size. Overall, line straightness for the walking condition was better than for the standing condition (Figure 5.3). For the rest of the values, there was no significant main effect between movement types and spatial ability groups (Table 1).

*Shape likeness:* We subjectively compared the similarity of the sketch to the 3D model following the Cohen and Bennett [12] definition of shape likeness, which attempts to remove aesthetics from the evaluation. To do so we used a variant of the card-sort method. The scoring was done inside a virtual environment using the Unity3D strokes created by the users and the 3D model as an example. First, we standardized the sketches' sizes by scaling the drawings to the same height while keeping the same proportions. We also rotated the drawings to match the top two corners of the 3D model used to create the target image (Figure 4). Then, each drawing was given a qualitative score between 10 (very good) and 1 (very poor) 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/absence of shape features, i.e., missing elements, extra elements, and rotating elements. Each drawing was first scored by comparing to the other drawings by the same participant. Then we compared each individual drawing to drawings with similar scores and standardized the scores across the users. Similar subjective shape-likeness scoring methods have been used by Tchalenk [51] and Chamberlain [10]. There was a significant main effect of spatial ability on shape likeness ($F_{1, 10} = 13.5$, $p = 0.004$). Cohen's $d = 0.9$ identifies a large effect size. Shape likeness for the HSA participants was significantly higher than for the LSA participants (Figure 5.4).

*3D drawing behaviours:* We identified differences in the way a user creates the strokes and how they move while drawing. For this, we only evaluated the drawings made in the walking condition, as this condition is the one that mimics a *real* immersive 3D drawing tool. All participants moved in this condition. As looking only at this condition removes half of our data, we re-analyzed the line-precision and shape-likeness scores to see if the same effects occur as with the full data. The user's spatial ability has a statistically significant effect on shape likeness ($F_{1, 34} = 11.45$, $p = 0.0001$), as HSA shape-likeness scores were higher than LSA shape-likeness scores. Cohen's $d = 0.7$ identifies a large effect size. There is also a statistically significant effect on line precision ($F_{1, 34} = 10.58$, $p = 0.002$), with HSA line precision being higher than LSA line precision. Cohen's $d = 0.4$ identifies a large effect size. We discuss this difference below.

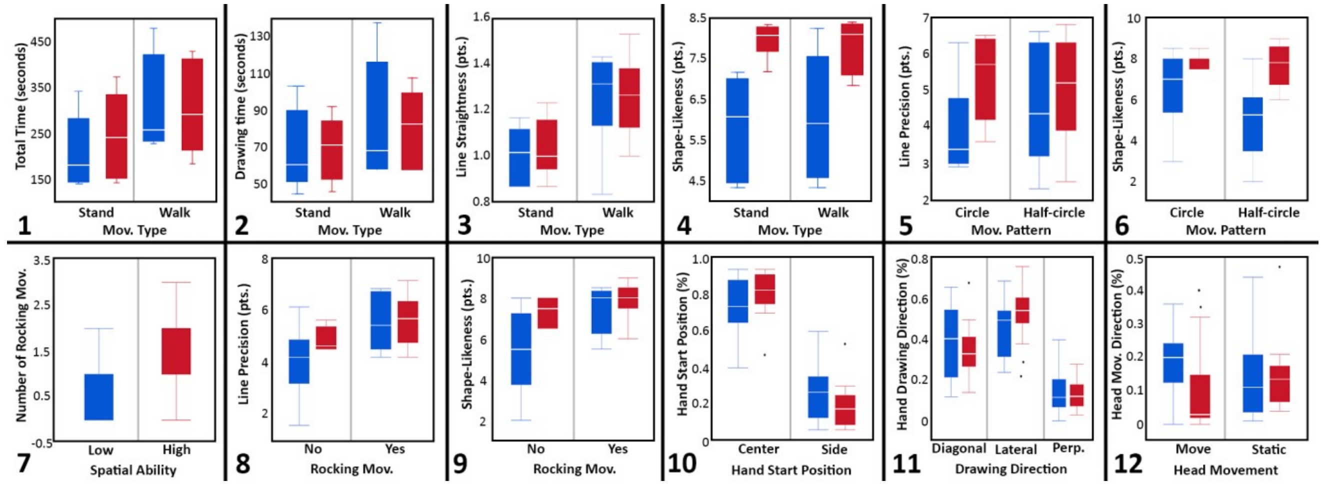


**Figure 5. Experiment 1 results, 1) total time, 2) drawing time, 3) line straightness, 4) shape likeness, and 5-12) drawing behaviours.**

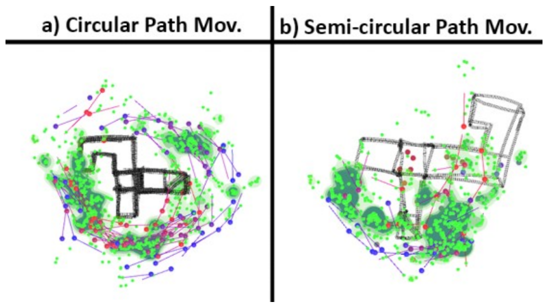


**Figure 6. Allegory movement paths for standing position from a top view. Green areas are the user standing positions, red-to-blue gradient dots represent the participant's movement.**

*Standing positions while drawing:* We identified the different positions where the participants stood while drawing to identify the number of viewpoints from which they saw their drawing. To get this data, we created heat maps of the participants' head positions while drawing. In the heat maps, each head position had a weight of 0.1 pts and a circular area of 10 cm radius; see Figure 6. From these heat maps, we identified three different types of patterns: two view positions, circular movement paths, and semi-circular movement paths. The two-view pattern was used only by two HSA participants for shape 1, so we removed this pattern from the following analysis. For the remaining 34 drawings, 19 follow a circular movement path (Figure 6a), and 15 follow a semi-circular path (Figure 6b).

When analyzing the movement patterns, we found a statistically significant effect on shape-likeness scores between HSA and LSA participants ($F_{1, 34} = 11.7$, $p = 0.0001$). Cohen's $d = 0.29$ identifies a medium effect size. Overall, HSA participants got better shape-likeness scores than LSA participants for both movement types (Figure 5.6). There is also a marginally significant effect on shape likeness between the participant's spatial ability and movement type ($F_{1, 34} = 2.92$, $p = 0.09$). Both participant groups achieved better shape-likeness scores when using the circular pattern than the half-circle pattern, but in both conditions' HSA shape-likeness scores were higher. Finally, there is a marginally significant effect on line-precision scores between HSA and LSA participants ($F_{1, 34} = 3.68$, $p = 0.06$). HSA participants have better line precision than LSA participants (Figure 5.5).

*Movement paths:* We analyzed the participant's head position over time to see how the participants moved while drawing. To get this data, we first identified head positions that were at least 30 cm from the previous position to eliminate head movements without walking. Then we used a red-to-blue gradient to visualize which positions were used first and which last (Figure 6). Shades of red represented the first positions and blue the last. We found that some participants orbit around part of their drawing before moving to another part, and we called this behaviour *rocking movement*. There is a statistically significant in the number of rocking movements between HSA and LSA participants ($F_{1, 34} = 11.45$, $p = 0.0001$). Cohen's $d = 0.59$ identifies a large effect size. HSA participants did more rocking movements than LSA participants (Figure 5.7).

We also analyzed the shape-likeness and line-precision results between participants that used rocking and those that did not. There is a statistically significant effect on the shape-likeness scores between participant that rocked and those that not ($F_{1, 30} = 11.6$, $p = 0.002$). Cohen's $d = 0.57$ identifies a large effect size. Participants that used rocking achieved better shape-likeness scores than those participants that did not (Figure 5.9). There is also a statistically significant effect on line precision between participant that rocked and those that not ($F_{1, 30} = 10.58$, $p = 0.002$). Cohen's $d = 0.55$ identifies a large effect size. Here, participants that used rocking got better line-precision scores than those participants that did not (Figure 5.8). However, we did not find a difference in terms of line precision or shape likeness based on the participant's spatial ability, nor an interaction between spatial ability and rocking.

*Hand starting position:* We analyzed the hand's starting position for each stroke to identify whether the users' spatial ability affected their arm movement relative to their head position. To get this data, we manually tagged the screen capture of the session and recorded the percentage of strokes that were part of different groups. We found two different types of hand starting position, middle and side. For a hand-starting-position in the middle, participants started the stroke near the vertical midline of their bodies and moved their hand away from the center. In a side-hand-starting position, participants started the stroke on one side of their body and moved their hand across their body. There is a statistical significance in the percentage of strokes that were part of each group ($F_{1, 10} = 52.31$, $p = 0.0001$). Cohen's $d = 1.5$ identifies a large effect size. A majority of the participants started a stroke in the center of their body rather than on the side of their body (Figure 5.10). However, there was neither a significant difference between HSA and LSA participants nor an interaction between spatial ability and hand position.

*Drawing direction:* We analyzed the way each participant moved their hand when drawing strokes, based on their body position, to identify how frequently participants drew strokes perpendicular to the view plane. Other drawing movements might be lateral/vertical in the drawing plane or a mixture of both, being diagonal in depth. To analyze drawing directions, we manually tagged the screen capture of each session and recorded the percentage of strokes that were part of each group. We used the participant's current view to identify their drawing direction. We did not use the head position, as this may not represent the body orientation accurately. We found three different types of drawing directions: a) lateral, b) diagonal, and c) perpendicular. In the lateral drawing direction participants moved their hand approximately parallel to the view plane, in diagonal participants moved their hand approximately at a 45° angle from the view direction, and in the perpendicular drawing direction participants moved their hand approximately along the view direction, i.e., perpendicular to the view plane.

There is a statistically significant difference in the percentage of strokes that belong to each category ($F_{2, 20} = 38.03$, $p = 0.0001$). Cohen's $d = 1.1$ identifies a large effect size. A Tukey-Kramer post-hoc test showed that the lateral direction was more frequently used than diagonal and perpendicular directions ($p = 0.0001$), for 49% of all drawing movements. The diagonal direction was also more frequent than the perpendicular direction ($p = <.0001$), with 37% of all the drawing movements. Finally, the perpendicular direction was used infrequently, with only 14% of the drawing movements (Figure 5.11). We could not identify a difference in the percentage of strokes that belong to each category between HSA and LSA participants, nor an interaction between spatial ability and drawing direction category.

*Head movement while drawing:* We analyzed whether the head followed the hand while doing the stroke or not, to identify if there are differences in eye-hand coordination between HSA and LSA participants. To get this data, we manually tagged the screen capture of the session and recorded the percentage of strokes for which the head followed the hand. We could only identify a marginally significant interaction between spatial ability and head movement ($F_{1, 10} = 3.4$, $p = 0.07$). More participants kept their head static while drawing, but for the participants that moved their head, LSA participant moved their head while drawing more than HSA participants (Figure 5.12).

## Discussion

*Shape likeness**:*** Overall, HSA participants draw shapes that are more like the 3D models than LSA participants. For example, for Shape 2 the difference is almost 1.9 pts in ratings between the groups (HSA = 7.7 pts. vs. LSA = 5.8 pts.). The difference in scores is also visible when just considering the walking condition. These findings support our hypothesis ***H1***, as participants with high spatial ability achieved better scores for shape likeness compared to low spatial ability participants. One probable reason behind a difference in drawing scores is the participants drawing experience, however, when analyzing the 2D drawing experience between both groups we found that participants had similar drawing experiences ($F_{1,11} = 0.19$, $p =$ N.S.). When analyzing the effect of the different types of movements, we did not find a significant effect on the shape likeness to the 3D model. The observed lack of impact of walking on shape likeness is the opposite of what previous literature on the cognitive effort of walking reports [59].

*Line precision:* The overall line precision for both standing and walking conditions was not statistically different between the HSA and LSA groups. There were significant low scores for line straightness in the standing condition, but those can be related to the naturally curved arm movements of humans, which have been discussed before by Arora et al. [2] and are a consequence of the absence of a physical surface. One probable reason behind the similar scores is the difference in total time between movement types, but we consider this to be a consequence of the time spent moving in the walking condition. The statistical difference in drawing time means that participants spent less time creating strokes while standing. We do not have enough information to identify a reason for this difference, however we hypothesize that participants could not see the mistakes they were making, as they used only a single viewpoint. Overall, our results do not support hypothesis ***H2***. Interestingly, when only evaluating drawings created when walking, the line precision was significantly different between spatial ability groups. Notably, we found that the HSA participant's line precision was better than that for the LSA participants. The HSA participant's higher (3D) line precision scores while walking confirm the findings of previous work for 2D drawings [39].

*User's behaviours:* To better understand how a user plans their next stroke, we also analyzed the walking condition of our experiment in detail to identify the participants' drawing behaviours while drawing in 3D. In this condition, the participants were free to walk in any direction while drawing. First, we analyzed the users' *standing positions* around the drawn object. Most participants followed either a circular or a semi-circular movement pattern. Although there is only a marginally significant difference between these patterns regarding outcomes, there seems to be a tendency where a user's movement pattern and spatial ability affects the shape-likeness score. For example, HSA participants that followed a circular pattern had a slightly higher score (7.9 pts.) than the participants that followed a half-circle pattern (7.7 pts.). This effect is more pronounced for LSA participants (circle = 6.6 pts. vs half-circle = 5 pts.). In general, the circular pattern has a larger number of distinct viewpoints than the half-circle pattern. These results support previous work, where multiple views of an object helped users understand a 3D object better than with mental rotation [45], which is an important step of planning the next stroke.

We also analyzed the *movement paths* while drawing. Here we found that some participants performed the rocking movement explained before. This rocking movement allows participants to change perspectives continuously before making a stroke, which may help them plan that stroke better. In contrast, for both spatial ability groups, participants with low shape-likeness scores remained in the same position more often than high-score participants. Even if they used similar viewpoints, their movements around the drawing are also more chaotic (Figure 7). Using a rocking movement has a positive effect on the overall likeness of the score (Present = 7.7 pts. vs. Absent = 5.8 pts.) and on the line precision (Present = 5.7 pts vs Absent = 4.7 pts).

When analyzing the *hand movement direction*, we found a difference in the number of strokes each participant did in each category, with most participants using more lateral and diagonal drawing movements and fewer perpendicular movements. These results together with the movement patterns and the rocking movements lead us to believe that most participants were mostly performing planar drawings. When they needed to draw in depth, they preferred to move around rather than to draw with hand motion perpendicular to their view. This is an important finding because it shows that participants were actively avoiding perpendicular movements, even though the freedom to do this has been claimed as an advantage of 3D drawing [49]. Based on previous work we hypothesize that the reasons behind this deliberate behaviour are to work around depth perception problems [1, 6, 7, 42] and biomechanical limitations [36].

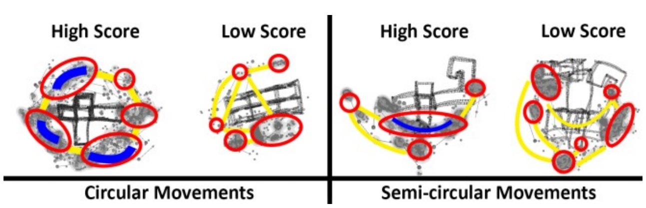


**Figure 7. Movement paths with rocking vs no rocking. The red shapes show areas where the user stood to draw, and the yellow lines show walking paths. The blue lines show rocking movements.**

The last two measures we evaluated were *hand start positions* for a stroke and *head movement* while drawing. For hand position, there was a significant difference on the percentage of stroke that started at each position between the categories (side = 0.23% vs center = 0.76%), but not between HSA and LSA participants. For head movement types there was no difference between spatial ability groups. These results lead us to believe that the participant's arm movement and their eye-hand coordination do not strongly correlate with the user's spatial ability. In conclusion, the participant's movement while drawing and the benefits of different movement patterns depends on the participant's spatial ability. These findings support our hypothesis ***H3***. However, we found no effect of a user's spatial ability on other behavioural methods used for 3D drawing, like drawing direction, hand starting positions and head movement while drawing.

*General Discussion:* Our first hypothesis was that a user's spatial ability affects the shape of their final sketch. We were able to confirm our ***H1***, as the shape likeness of the drawing is affected by the user's spatial ability. However, we did not find a difference in line precision. These results lead us to believe that the higher cognitive and sensorimotor demands of 3D drawing [57] affect HSA users less than LSA users. Our second hypothesis was that the shape likeness and line precision of users diminishes when they change their viewpoint while drawing. However, we found that the user line precision increased when walking, and we found no difference on shape likeness, which does not support hypothesis ***H2***.

While our results were only measured for geometrical shapes, we hypothesize that they also hold for more general drawings. It is as difficult to draw a straight line in an otherwise free-form drawing as it is to draw one that is part of a geometric shape. We performed a post hoc power analysis for each parameter, based on the mean, between-groups and within-groups comparison, and the effect size. It showed limited statistical power because of the modest sample size in the present study (N = 12) for the following results: drawing time (.40), shape likeness (.60), line precision (.24) for the walking condition, and shape likeness (.53) for the movement paths analysis. All other statistical results obtained statistical power at the recommended .80 level.

Based on these mixed results, and our analysis of the participant's drawing behaviours, we believe that user's spatial ability only affects certain classes of 3D drawing behaviours and that different classes of 3D drawing behaviours affect different parts of the stroke planning process and the stroke execution process. Those related to user movement while drawing, i.e., movement pattern and movement path, are correlated with shape likeness, as we found a significant difference between the shape-likeness scores of participants that use the rocking movement and those that do not. These behaviours are related to identifying an appropriate viewpoint to draw the next stroke. They are also related to the user's spatial ability, as HSA participants used such behaviours more than LSA participants. Those drawing 3D behaviours related to hand movements and eye-hand coordination, i.e., hand starting position and head movement, are not correlated to either the line precision or the shape likeness. These behaviours are related to positioning the hand in the correct place to draw the stroke. They are also individual to each participant, as the user's spatial ability did not influence them. Finally, the hand movement direction is part of the stroke creation process, not the planning phase. But it shows that the users carefully plan their standing position to avoid movements in depth.

## USER STUDY 2

In user study 1, we found that there are specific behaviours that help users select the correct viewpoint to draw the next stroke. Interestingly, one of our findings contradict previous work that changing the viewpoint through walking does not impact the shape-likeness scores. This result motivated us to further study the effect of changing the viewpoint while drawing in VR. Based on this, we hypothesize (***H4***) that *a user's line precision and shape likeness is affected by the viewpoint method used while drawing.* We expect that drawing while walking improves the user's line precision and shape likeness compared with other viewpoint-control methods. Therefore, we evaluated the effect of using two common hand-based viewpoint control methods currently used in 3D immersive drawing systems:

*Two-hand rotation (THR):* We implemented a variation of the *grab the air* interaction technique [44], where the user uses both controllers to grab the world and rotate it. Our implementation uses the position between both controllers as the rotation pivot. As we are comparing this method with walking, we only allow users to do a 1DOF rotation around the world up vector. Our technique also allowed for a 3DOF translation of the object.

*One-hand rotation (OHR):* We mapped the sketch rotation to the left controller pose and let users rotate it and translate it by moving the controller. Again, we only allowed 1DOF rotation to emulate walking.

## METHODOLOGY

### *Participants*

We recruited 12 participants from the university community (4 female). 5 of the participants were between 18-20 years old, 3 were between 21-24 years old, and 4 were between 25-30 years old. None of the participants took part in study 1. The participants' frequency of drawing with pen and paper was that 4 draw a few times a week, 2 every week, 3 a few times a month, 1 once a month, and 2 less than once a month. For drawing in VR, only 2 participants had drawn in VR before. We measured the participants' spatial abilities before they drew as we did in the first study; the participants were equally divided between high and low spatial ability.

### *Apparatus & Procedure*

The hardware setup was identical to study 1. The 3D software was updated to allow users to rotate their sketches. As in the previous experiment, users used their dominant hand to draw the strokes with the freehand drawing technique. The experiment procedure was identical to study 1, and the target shapes were Shape 2 and 3 of study 1 (Figure 3).

### Design

The study used a 3x2x2 mixed design. The within-subjects independent variables were the movement type (walking, OHR, THR) and the drawing shape (2, 3). The between-subjects independent variable was the user's spatial ability (low vs. high). In total, we collected 72 drawings, 6 for each participant. Because there were the same number of participants in both ability groups, our design was balanced between factors. The order of conditions across within-subject dimensions was counter-balanced across participants following a Latin-square design. The collected measures were drawing time (seconds), total time (seconds), the stroke objects in Unity3D, and the participant's head and hand position. We also recorded video of the participants and created a screen video of the participants' view while drawing.

### Results

The results were analyzed using repeated measures ANOVA with $\alpha=0.05$. All the data were normally distributed, except for drawing time and shape likeness. To normalize that data we used ART [58] before the ANOVA. Statistical results are reported in Table 2, where "***" marks results with $p < 0.001$, "**" for $p < 0.01$, "*" for $p < 0.05$, "M.S." for marginally significant, and "N.S." for not significant. Figure 8 shows some of the resulting 3D drawings done by our participants.

*Total Time:* There was no significant difference between spatial ability groups or movement types for total time.

*Drawing time:* There was no significant difference between spatial ability groups or movement types on drawing time.

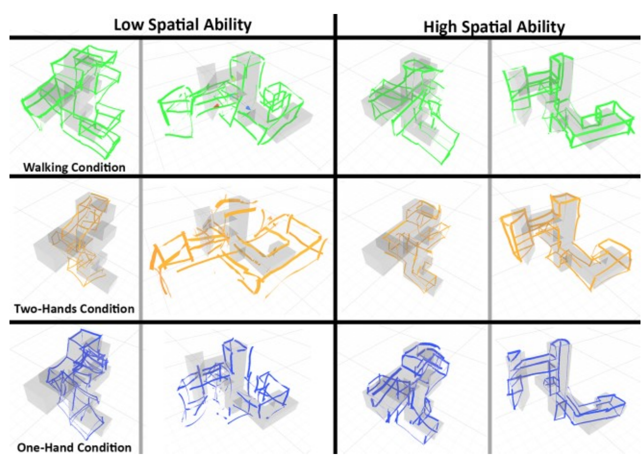


**Figure 8. Study 2 results.**

*Line precision:* We coded each drawing using the same method as in study 1. There was a significant main effect of movement type on the matching of line pairs ($F_{2, 20} = 4.8$, $p = 0.019$), but not between spatial ability groups. Cohen's $d = 0.19$ identifies a small effect size. A post-hoc analysis showed a difference between using THR and walking ($p = 0.02$), but not between OHR and walking or OHR and THR (Figure 9.1). There was also a significant main effect of movement type on the stroke's degree of deviation ($F_{2, 20} = 6.5$, $p = 0.006$), but not for spatial ability. Cohen's $d = 0.31$ identifies a medium effect size. A post-hoc analysis identified a difference between using THR and walking ($p = 0.0056$), but not between OHR and walking or OHR and THR (Figure 9.2). For the rest of the line-precision categories, there was no significant main effect between movement types and spatial ability groups.

*Shape likeness:* We again coded 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 ($F_{1, 10} = 6.5$, $p = 0.02$). Cohen's $d = 0.6$ identifies a large effect size. Shape-likeness scores for HSA participants were significantly higher than LSA participants' scores (Figure 9.3). There was also a significant main effect of movement type on shape likeness ($F_{2, 20} = 32.2$, $p < 0.001$). Cohen's $d = 1.77$ identifies a large effect size. A Bonferroni correction post-hoc analysis identified each movement type in a different group, where walking was better than THR, and THR was better than OHR. There was a significant main effect on shape likeness between movement type and spatial ability ($F_{2, 20} = 3.6$, $p = 0.047$). For HSA participants a post-hoc analysis identified a difference between using OHR and walking ($p = 0.0006$). For LSA participants, all rotation methods were statistically significantly different from each other (Table 2 and Figure 9.3).

| | SPATIAL ABILITY | | MOVEMENT | | MOVEMENT ✕ SPATIAL ABILITY | |
|---|---|---|---|---|---|---|
| ***MEASURE*** | ***F (1, 10)*** | ***p*** | ***F(2, 20)*** | ***p*** | ***F (2, 20)*** | ***p*** |
| TOTAL TIME | 3.13 | N.S. | 3.07 | M.S. | 1.8 | M.S. |
| DRAWING TIME | 0.63 | N.S. | 2.34 | N.S. | 0.016 | N.S. |
| LINE STRAIGHTNESS | 0.46 | N.S. | 1.48 | N.S. | 0.54 | N.S. |
| MATCHING OF LINE PAIRS | 2.8 | N.S. | 4.8 | * | 2.9 | M.S. |
| DEGREE OF DEVIATION | 0.13 | N.S. | 6.5 | ** | 1.26 | N.S. |
| CORRECTIVE MOVEMENTS | 0.13 | N.S. | 0.24 | N.S. | 2.2 | N.S. |
| SHAPE LIKENESS | 6.5 | * | 32.2 | *** | 3.56 | * |

**Table 2. User study 2 statistical results**

## Discussion

*Shape likeness:* We found a difference between movement types, where walking was better than THR, and THR was better than OHR. There were no significant differences for drawing or total time, which shows that the time spent drawing is unlikely to be a cause for this difference. These results show that the viewpoint control method has an effect on user performance. Specifically, it shows that walking is better for keeping the shape likeness of the sketch than hand-based viewpoint control methods. Based on this, we hypothesize the similar results of standing and walking in study 1 are a consequence of the positive effects of physical moving on spatial updating, which helps users to remain oriented in space [33]. Thus, users can more easily find the correct viewpoint to draw their next stroke. Finally, the interaction between movement type and spatial ability, where the movement type affected HSA less than LSA participants, verifies previous work on spatial ability [23, 34].

*Line precision:* We found that the movement type has a significant effect on line precision for the matching of line pairs and the stroke degree of deviation. These line precision categories are related to positioning the stroke in place, which confirms that depth perception issues affect 3D drawing. It also makes us hypothesize that spatial orientation also affects line precision. The post hoc analysis shows that walking is better than THR. The lack of significance between walking and OHR made us look at the data in more depth. We found that participants used a similar number of scene rotations in the OHR and THR conditions ($F_{1, 10} = 0.01$, $p =$ N.S.), but when looking at the screen capture videos, the OHR rotations seem to have involved smaller angles than the THR rotations. Based on this, we speculate that these small OHR rotations might have been less disorienting than the larger THR rotations. Overall, these results show that for immersive 3D drawing walking is better than hand-based view control.

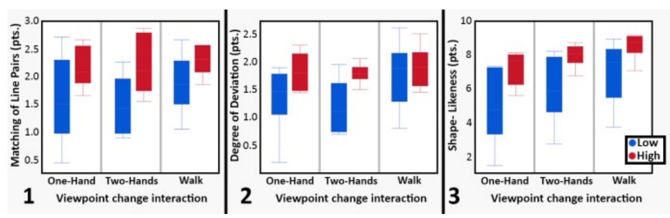


**Figure 9: Experiment 2 results, 1) matching of line pairs, 2) degree of deviation, and 3) shape likeness.**

*General Discussion:* We analyzed the effects of viewpoint change on stroke planning. We found that users achieved better shape likeness and line precision scores when walking than when using hand-based viewpoint control. We hypothesize that this difference is a consequence of better spatial updating when walking [33], which help users better orient themselves in space than when using hand-based viewpoint control methods. These results validate previous work, where the viewpoint control method has an effect on user performance [35, 55], but also extends this work to 3D immersive drawing. Our results also show the importance of choosing the correct viewpoint control method, as we found that both line precision and shape likeness are affected by it. We hypothesize that the reason behind this is related to the selection of a wrong viewpoint due to disorientation. Based on this, the higher degree of spatial orientation of HSA participants compared to LSA participants in study 1 may be the reason for their high line precision scores in the walking condition. However, such speculations need to be verified in future work. We were also able to confirm the outcomes of our study 1 results, i.e. that the shape likeness of the drawing is affected by the user's spatial ability, but not line precision. This confirms our ***H1***. We were also able to show that hand-based viewpoint control methods affect the user's line precision and shape likeness, which confirms our ***H4***. However, we found that the user's spatial ability can diminish this effect, based on the interaction between spatial ability and movement type on shape likeness. In conclusion, the results of study 2 further support the findings of study 1 on the user's behaviours, as selecting the correct viewpoint is not only important for the shape likeness, but also for the sketches' line precision. Finally, limited statistical power because of the modest sample size in the present study (N = 12) may have played a role in limiting the significance of some of the statistical comparisons conducted. A post hoc power analysis, based on the mean and the between-groups and within-groups comparison effect size, revealed that the following statistical results had a limited statistical power: the matching of the line pairs (0.25), degree of deviation (0.58), line precision (0.51) and shape likeness (0.50). Other results obtained a statistical power at the recommended .80 level.

## USER INTERFACES TO SUPPORT IMMERSIVE 3D DRAWING

Based on the results of our two studies, we present several recommendations for 3D immersive drawing interfaces:

### *Encourage users to change their viewpoint.*

Moving is critical for 3D drawing, since it allows users to view their drawing from different viewpoints and better plan their next stroke. In study 1 we identified that walking avoids the creation of accidentally curved strokes regardless of user spatial ability, which Arora et al. [2] identified to be a problem with drawing when standing. In study 2 we identified that the viewpoint control method affects the shape likeness, because when users changed their view using hand-based viewpoint control methods their shape-likeness scores were lower than when they walked around their drawing. This is related to spatial ability, as HSA users achieved better shape-likeness scores than LSA users. Therefore, a 3D drawing user interface needs to encourage users to walk around their drawings to make it easier to identify the "real" stroke shape in 3D.

### *Help users identify the spatial relationship between strokes*

Previous work [30] found that repositioning the view increases 3D understanding of the shape. Study 1 and 2 complement these results by showing that understanding the global shape of the sketch is related to systematically moving around the drawing while maintaining a good spatial orientation. More importantly, we identified that regardless of the user's spatial ability, using rocking movements around the drawing improved their shape-likeness scores, as such rocking helps to perceive the correct spatial relation of a new stroke relative to existing content. Therefore, a 3D drawing user interface should help users understand the spatial relationship between strokes, such as orthogonality between strokes, better, e.g., by encouraging users to do rocking movements between drawing strokes.

### *Give users tools to maintain their orientation while changing the viewpoint*

In study 2 we found that one advantage of walking over other viewpoint control methods is its ability to help users keep themselves oriented in space. This is related to spatial ability, as HSA users achieved were less affected by the negative effects of using hand-based control methods than LSA users. However, it is not always possible to physically move to the correct viewpoint. Therefore, a 3D drawing user interface should help LSA users better understand the spatial relationship between strokes, such as orthogonality between strokes, by providing strong orientation cues or navigation aids that show the probable position of new strokes in relation to the current strokes.

### *Give users tools to draw in depth*

In study 1, we found that most users preferred lateral hand movements over depth movements. However, using only lateral hand movements negates one of the advantages of drawing in 3D, the ability to draw in depth. Therefore, we suggest giving users tools to improve depth perception to encourage depth hand movements. Another advantage of providing extra tools to better perceive depth is that it may help users identify the correct hand position in space, which may improve line precision as found in study 2. Previous work [2] suggested the use of planar surfaces to avoid problems related to depth perception and motions while drawing in VR. We complement their advice, by suggesting the use of widgets and visual guides inside the virtual environment to provide extra depth cues.

## CONCLUSION

This paper quantifies the effect of spatial ability on 3D drawing. Our findings show that the user's spatial ability affects the shape likeness of their sketches but not their line precision, as high-spatial-ability users achieve better shape-likeness scores than low-spatial-ability users. This is particularly interesting since previous literature [14, 39] has not identified such an effect. More importantly, we found different types of user behaviours while drawing in 3D in study 1. Those related to the shape likeness are about identifying the correct viewpoint to draw the next stroke. Other behaviours are related to line precision and help users correctly position their hand in space to start a stroke. In study 2, we found that choosing the correct viewpoint also has a positive effect on line precision. In future work, we plan to explore the effect of disorientation on line precision and shape likeness further.

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## REFERENCES

[1] Armbrüster, C. et al. 2008. Depth Perception in Virtual Reality: Distance Estimations in Peri- and Extrapersonal Space. *CyberPsychology &*

*Behavior*. 11, 1: 9–15. https://doi.org/10.1089/cpb.2007.9935.

[2] Arora, R. et al. 2017. Experimental Evaluation of Sketching on Surfaces in VR. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '17), 5643–5654. https://doi.org/10.1145/3025453.3025474.

[3] Arora, R. et al. 2018. SymbiosisSketch : Combining 2D & 3D Sketching for Designing Detailed 3D Objects in Situ. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '18), 1–15. https://doi.org/10.1145/3173574.3173759.

[4] Baker Cave, C. and Kosslyn, S.M. 1993. The role of parts and spatial relations in object identification. *Perception*. 22, 2: 229–248. https://doi.org/10.1068/p220229.

[5] Barrera Machuca, M.D. et al. 2018. Multiplanes: Assisted freehand VR Sketching. *Proceedings of the ACM Symposium on Spatial User Interaction* (SUI'18), 36–47. https://doi.org/10.1145/3267782.3267786.

[6] Barrera Machuca, M.D. and Stuerzlinger, W. 2019. The Effect of Stereo Display Deficiencies on Virtual Hand Pointing. *Proceedings of SIGCHI Conference on Human Factors in Computing Systems Proceedings* (CHI '19), 14. https://doi.org/10.1145/3290605.3300437

[7] Batmaz, A.U. et al. 2019. Do Head-MountedDisplay Stereo Deficiencies Affect 3D Pointing Tasks in AR and VR? *IEEE Conference on Virtual Reality and 3D UserInterfaces* (VR '19).

[8] Bowman, D.A. et al. 1997. Travel in immersive virtual environments: an evaluation of viewpoint motion control techniques. *Proceedings of IEEE 1997 Annual International Symposium on Virtual Reality* (VR' 97), 45–52. https://doi.org/10.1109/VRAIS.1997.583043

[9] Branoff, T. and Dobelis, M. 2013. The Relationship Between Students' Ability to Model Objects from Assembly Drawing Information and Spatial Visualization Ability as Measured by the PSVT:R and MCT. *ASEE Annual Conference Proceedings* (ASEE '013).

[10] Chamberlain, R. et al. 2011. The Perceptual Foundations of Drawing Ability. *Proceedings of an interdisciplinary symposium on drawing, cognition and education*, 95–10.

[11] Christou, C.G. et al. 2003. Extrinsic cues aid shape recognition from novel viewpoints. *Journal of Vision*. 3, 3: 183-198. https://doi.org/ 10.1167/3.3.1.

[12] Cohen, D.J. and Bennett, S. 1997. Why Can't Most People Draw What They See? *Journal of Experimental Psychology: Human Perception and Performance*. 23, 3: 609–621. https://doi.org/10.1037/0096-1523.23.3.609.

[13] Deering, M.F. 1996. The HoloSketch VR sketching system. *Communications of the ACM*. 39, 5 : 54–61. https://doi.org/10.1145/229459.229466.

[14] Dünser, A. et al. 2006. Virtual and augmented reality as spatial ability training tools. *Proceedings of the ACM SIGCHI New Zealand chapter's international conference on Computer-human interaction: design centered HCI* (CHINZ '06), 125–132. https://doi.org/10.1145/1152760.1152776.

[15] Ekstrom, R.B. et al. 1976. Manual for kit of factor-referenced cognitive tests. *Princeton NJ Educational Testing Service*. 102, 41: 117. https://doi.org/ 10.1073/pnas.0506897102.

[16] Facebook 2018. Quill.

[17] La Femina, F. et al. 2009. A battery for the assessment of visuo-spatial abilities involved in drawing tasks. *Clinical Neuropsychologist*. 23, 4: 691–714. https://doi.org/10.1080/13854040802572426.

[18] Fiorentino, M. et al. 2003. 3D Sketch Stroke Segmentation and Fitting in Virtual Reality. *International Conference on the Computer Graphics and Vision* (CGV '03), 188–191.

[19] Fitzmaurice, G. et al. 2008. Safe 3D navigation. *Proceedings of the 2008 symposium on Interactive 3D graphics and games* (SI3D '08), 7. https://doi.org/ 10.1145/1342250.1342252.

[20] Google 2016. Tilt Brush.

[21] Gowen, E. and Miall, R.C. 2006. Eye-hand interactions in tracing and drawing tasks. *Human Movement Science*. 25, 4–5: 568–585. https://doi.org/10.1016/j.humov.2006.06.005.

[22] Grossman, T. et al. 2002. Creating principal 3D curves with digital tape drawing. *Proceedings of the SIGCHI conference on Human factors in computing systems Changing our world, changing ourselves* (CHI '02), 121. https://doi.org/10.1145/503376.503398

[23] Hegarty, M. and Waller, D. 2004. A dissociation between mental rotation and perspective-taking spatial abilities. *Intelligence*. 32, 2: 175–191. https://doi.org/10.1016/j.intell.2003.12.001.

[24] Hess, R.F. et al. 2015. Stereo Vision: The Haves and Have-Nots. *i-Perception*. 6, 3: 1–5. https://doi.org/10.1177/2041669515593028.

[25] HTC 2016. VIVE.

[26] Israel, J.H. et al. 2009. Investigating three-dimensional sketching for early conceptual

design—Results from expert discussions and user studies. *Computers & Graphics*. 33, 4: 462–473. https://doi.org/10.1016/j.cag.2009.05.005.

[27] Jackson, B. and Keefe, D.F. 2016. Lift-Off: Using Reference Imagery and Freehand Sketching to Create 3D Models in VR. *IEEE Transactions on Visualization and Computer Graphics*. 22, 4: 1442–1451. https://doi.org/10.1109/TVCG.2016.2518099.

[28] Jin, Y. and Chusilp, P. 2006. Study of mental iteration in different design situations. *Design Studies*. 27, 1: 25–55. https://doi.org/10.1016/j.destud.2005.06.003.

[29] Keefe, D.F. et al. 2001. CavePainting: A Fully Immersive 3D Artistic Medium and Interactive Experience. *Proceedings of the ACM Symposium on Interactive 3D Graphics* (I3D '01), 85–93. https://doi.org/http://doi.acm.org/10.1145/364338.364370.

[30] Keefe, D.F. et al. 2007. Drawing on Air: Input Techniques for Controlled 3D Line Illustration. *IEEE Transactions on Visualization and Computer Graphics*. 13, 5: 1067–1081. https://doi.org/10.1109/TVCG.2007.1060.

[31] Kenyon, R. V. and Ellis, S.R. 2014. *Virtual Reality for Physical and Motor Rehabilitation*. Springer New York. https://doi.org/10.1007/978-1-4939-0968-1.

[32] Khan, A. et al. 2008. ViewCube. *Proceedings of the 2008 symposium on Interactive 3D graphics and games* (SI3D '08), 17. https://doi.org/10.1145/1342250. 1342253.

[33] Klatzky, R.L. et al. 1998. Spatial Updating of Self-Position and Orientation During Real, Imagined, and Virtual Locomotion. *Psychological Science*. 9, 4: 293–298. https://doi.org/10.1111/1467-9280.00058.

[34] Kozhevnikov, M. and Hegarty, M. 2001. A dissociation between object manipulation spatial ability and spatial orientation ability. *Memory and Cognition*. 29, 5: 745–756. https://doi.org/10.3758/BF03200477.

[35] Lages, W.S. and Bowman, D.A. 2018. Move the Object or Move Myself? Walking vs. Manipulation for the Examination of 3D Scientific Data. *Frontiers in ICT*. 5: 1–12. https://doi.org/10.3389/fict.2018.00015.

[36] McDonald, A. et al. 2012. Spatial dependency of shoulder muscle demands in horizontal pushing and pulling. *Applied Ergonomics*. 43, 6: 971–978. https://doi.org/10.1016/j.apergo.2012.01.005.

[37] Murugappan, S. et al. 2009. Towards beautification of freehand sketches using suggestions. *Proceedings of the 6th Eurographics Symposium on Sketch-Based Interfaces and Modeling* (SBIM '09), 69. https://doi.org/10.1145/1572741.1572754.

[38] Oculus 2016. Rift.

[39] Orde, B.J. 1997. Drawing as Visual-Perceptual and Spatial Ability Training. *Proceedings of Selected Research and Development Presentations at the 1997 National Convention of the Association for Educational Communications and Technology*.

[40] Perkunder, H. et al. 2010. Shape Modeling with Sketched Feature Lines in Immersive 3D Environments. *Proceedings of the Eurographics Symposium on Sketch-Based Interfaces and Modeling (Expressive'10)*, 127–134.

[41] Pittalis, M. and Christou, C. 2010. Types of reasoning in 3D geometry thinking and their relation with spatial ability. *Educational Studies in Mathematics*. 75, 2: 191–212. https://doi.org/10.1007/s10649-010-9251-8.

[42] Renner, R.S. et al. 2013. The perception of egocentric distances in virtual environments - A review. *ACM Computing Surveys*. 46, 2: 1–40. https://doi.org/10.1145/2543581.2543590.

[43] Riecke, B.E. et al. 2007. Spatial Updating in Virtual Reality: The Sufficiency of Visual Information. *Psychological Research*. 71, 3: 298–313. https://doi.org/10.1007/s00426-006-0085-z.

[44] Robinett, W. and Holloway, R. 1992. Implementation of flying, scaling and grabbing in virtual worlds. *Proceedings of the 1992 symposium on Interactive 3D graphics* (SI3D '92), 189–192. https://doi.org/ 10.1145/147156.147201.

[45] Rock, I. et al. 1989. Can we imagine how objects look from other viewpoints? *Cognitive Psychology*. 21, 2: 185–210. https://doi.org/10.1016/0010-0285(89)90007-8.

[46] Samsudin, K. et al. 2016. Training in Mental Rotation and Spatial Visualization and Its Impact on Orthographic Drawing Performance. *Journal of Educational Technology and Society*. 14, 1:179-186.

[47] Shelton, A.L.M.Y.L. and McNamara, T.P. 1997. Multiple views of spatial memory. *Psychonomic Bulletin & Review*. 4, 1: 102–106. https://doi.org/10.3758/BF03210780.

[48] Shepard, R.N. and Metzler, J. 1971. Mental Rotation of Three-Dimensional Objects. *Science*. 171, 3972: 701–703. https://doi.org/10.1126/science.171.3972.701.

[49] Tano, S. et al. 2013. Truly useful 3D drawing system for professional designer by "life-sized and operable" feature and new interaction. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture*

*Notes in Bioinformatics)*. 8117 LNCS, PART 1: 37–55. https://doi.org/10.1007/978-3-642-40483-2_3.

[50] Tarr, M.J. et al. 1998. Three-dimensional object recognition is viewpoint dependent. *Nature Neuroscience*. 1, 4: 275–277. https://doi.org/10.1038/1089.

[51] Tchalenko, J. 2009. Segmentation and accuracy in copying and drawing: Experts and beginners. *Vision Research*. 49, 8: 791–800. https://doi.org/10.1016/j.visres.2009.02.012.

[52] Teramoto, W. and Riecke, B.E. 2010. Dynamic visual information facilitates object recognition from novel viewpoints. *Journal of Vision*. 10, 13: 1–13. https://doi.org/10.1167/10.13.11.Introduction.

[53] Tramper, J.J. and Gielen, S. 2011. Visuomotor coordination is different for different directions in three-dimensional space. *The Journal of Neuroscience*. 31, 21: 7857–7866. https://doi.org/10.1523/JNEUROSCI.0486-11.2011.

[54] Ullman, D.G. et al. 1990. The importance of drawing in the mechanical design process. *Computers & Graphics*. 14, 2: 263–274. https://doi.org/ 10.1016/0097-8493(90)90037-X.

[55] Usoh, M. et al. 1999. Walking -> Walking-in-Place -> Flying, in Virtual Environments. *Proceedings of the Conference on Computer Graphics and Interactive Techniques* (SIGGRAPH '99), 359–364. https://doi.org/ 10.1145/311535.311589.

[56] Wesche, G. and Seidel, H.-P. 2001. FreeDrawer: A Free-Form Sketching System on the Responsive Workbench. *Proceedings of the ACM Symposium on Virtual Reality Software and Technology* (VRST '01), 167. https://doi.org/10.1145/ 505008.505041.

[57] Wiese, E. et al. 2010. Investigating the learnability of immersive free-hand sketching. *Proceedings of the Seventh Sketch-Based Interfaces and Modeling Symposium* (SBIM'10), 135–142.

[58] Wobbrock, J.O. et al. 2011. The aligned rank transform for nonparametric factorial analyses using only anova procedures. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '11), 143. https://doi.org/10.1145/1978942.1978963.

[59] Yogev-Seligmann, G. et al. 2008. The role of executive function and attention in gait. *Movement Disorders*. 23, 3: 329–342. https://doi.org/10.1002/mds.21720.