Why move during virtual reality sketching? Experimental study to improve the quality of sketches in virtual reality

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Virtual Reality (VR) sketching is a valuable tool for conceptual understanding, creativity, and design, but quality issues can hinder its adoption. To address this, we conducted a study involving 15 novices and 15 experts who sketched three chair models in static, mobile, and control conditions. The results showed that mental rotation skills, training, model type, and movement impact sketch quality. The static condition negatively affected performance, particularly volume and proportion. Conversely, the mobile condition didn't improve sketch quality compared to the control group. 3D perception seems tied to movement, highlighting the need to adapt VR sketching software for these challenges. Enhancing the user experience and addressing these quality concerns will be pivotal in the widespread acceptance of VR sketching tools.

Keywords: virtual reality sketching, sketches, spatial inspection, self-motion, quality of the sketches, mental rotation

1 Introduction

Virtual Reality (VR) sketching, which allows users to draw 3D shapes in a virtual environment using freehand drawing, has become increasingly popular and useful in recent years, particularly in the early stages of design (Liao & She, 2023). Digital drawings allow for effective remote collaborations unlike traditional paper and pencil sketches (Pallot, 2011). They can be used for several use cases, including creativity tasks (e.g., Gong, Lee, Soomro, Nanjappan, & Georgiev, 2022; Yang & Lee, 2020), co-design processes (e.g., Fleury & Richir, 2021), Do-It—Together processes (e.g., Fleury, Poussard, et al., 2022), architecture (e.g., Gómez-Tone, Bustamante Escapa et al.,

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2021; Gómez-Tone, Martin-Gutierrez et al., 2021), researching design cognition (Neroni, Oti, & Crilly, 2021), design education (Horvat, Martinec, Lukačević, Perišić, & Škec, 2022), etc. Yang and Lee (2020) have shown that VR sketching boosts the creativity of designers in the ideation phase compared to a 2D interactive whiteboard (Houzangbe et al., 2022). These tools allow the extension of the design solution space, improve the transformation of ideas and encourage a holistic approach to design for concept generation (Yang & Lee, 2020). VR activities create a sense of presence that leads to better communication of the overall intentions of the designer (Schnabel, 2011). VR sketching also allows sketches to be viewed from other perspectives because users can move around the three-dimensional sketch (Milovanovic et al., 2017). This spatial context leads users to think about more connections between design solutions and helps synthesize design ideas into structured concepts (Murugappan & Ramani, 2010). Gómez-Tone, Bustamante Escapa et al. (2021) maintain that VR sketching allows the creation of an "ideal scenery in which sight, hands, and body work holistically." Van Goethem et al. (2020) explain that VR sketching can foster better satisfaction, efficiency, effectiveness, ease of use and enjoyment. To sum up, VR sketching provides exciting alternatives for creating and expressing new design ideas and communicating visually.

VR sketching is no longer limited to designers but is also used by the public for collaborative design projects (e.g., Fleury, Dupont, et al., 2022; Neroni et al., 2021). It is therefore important to make sure that it is easy to use for a large audience that is new to VR sketching. However, VR sketching also has its drawbacks and the use of this technology can be very complex, especially for the inexperienced (Chaniaud et al., 2023). VR systems are perceived as unsuitable by professional communication designers mainly due to the poor integration of software into the work of professionals (Laing & Apperley, 2020). The graphic designers interviewed for this study were concerned with the lack of connection between the real and the virtual. The participants in this study had to remove the headset or remember the details of the project while they were drawing. But, the most frequently reported limitation is the lack of accuracy (e.g., Arora et al., 2017; Machuca et al., 2019; Wiese, Israel, Meyer, & Bongartz, 2010). The lack of accuracy is detrimental to the creation process because the sketch may not match the user's intention (Barrera Machuca, Stuerzlinger, & Asente, 2019). The final look can be "rough" (Fleury, Dupont, et al., 2022). Indeed, most VR sketching software has no physical surface, unlike traditional sketching with paper and pencil (Arora et al., 2017). As a result, lines can be curved instead of straight, impacting the final look of the sketch. Users have no reference point and have to move around the sketch if they want to observe the arc of the lines. VR sketching requires depth perception which is also a source of error for users (Arora et al., 2017; Cave & Kosslyn, 1993; Tramper & Gielen, 2011). The lack of depth perception does not allow for a correct spatial representation (Cave & Kosslyn, 1993). Thus, sketching in VR requires motion and spatial inspection. Yang and Lee (2020, p. 1) point out that spatial inspection is a "key behavioral factor for sketching in VR." Barrera Machuca et al. (2019) explained that users have to use different views to plan their next hand movement. Chaniaud et al. (2023) showed that movement had an impact on the quality of VR sketches only on complex tasks and only for body position in the scene and not for headset rotation. The authors state that some participants move naturally while others stay put. All of these arguments seem to converge on the importance of considering the spatial environment, spatial inspection, movement and visuospatial abilities (e.g., Barrera Machuca et al., 2019; La Femina, Senese, Grossi, & Venuti, 2009; Obeid & Demirkan, 2020; Yang & Lee, 2020).

Other approaches can be taken to improve the use of VR sketching, particularly learning and training. Chaniaud et al. (2023) showed that VR experts perform better quality VR sketches compared to novices. In a study by Fleury, Dupont, et al. (2022), participants repeated the same task of VR sketching twice in two days and felt more comfortable on the second day. These results show that training seems to be an important element to consider for the use of VR sketching software. Gómez-Tone et al. (2021b) assumed that if the VR sketching is improved by training, it is due to the enhancement of visuospatial abilities (including mental rotation). These interpretations are in line with Farzeeha et al. (2017) who showed that prolonged use of the virtual learning environment could improve mental rotation skills. In contrast, Bolier, Hürst, van Bommel, Bosman, and Bosman (2018) found that the quality of VR drawings made by children improves over time but not their visuospatial abilities. There seems to be no clear consensus regarding the feasibility of enhancing visuospatial skills through sketching activities. Nevertheless, a correlation has been demonstrated that visuospatial skills improve the quality of sketches in VR. Chaniaud et al. (2023) showed that users with high mental rotation skills make more in-depth sketches. Thus, learning, training and spatial skills seem important abilities to consider in the quality of the VR sketching.

To sum up, VR sketching in 3D seems to be very demanding on the user's perception, motor skills, spatial inspection, visuospatial abilities and training. But is it possible to improve the quality of the VR sketches with a relevant approach supporting 3D perception in order to make the tool useable effectively by novices? The aim of this study is to analyze the effects of movement, mental rotation skills and training on the quality of the sketches. Based on the previously mentioned literature we can formulate four hypotheses (the two first hypotheses are replications of existing results (Chaniaud et al., 2023) in another context):

Firstly, we have previously observed that certain factors have an impact on VR sketching, especially mental rotation (visuospatial ability). Mental rotation skill has an impact on the quality of sketches (Alias, Gray, & Black, 2002; Barrera Machuca et al., 2019; Chaniaud et al., 2023; La Femina et al., 2009). Our first hypothesis was that the higher the mental rotation skill of the users, the higher the quality of VR sketching.

Secondly, according to its difficulty, the task models can have an impact on the quality of the sketches. For instance, some task models may be considered more difficult due to the curvature of the lines or because of other details. According to Chaniaud et al. (2023) a complex task requiring a greater level of detail is more difficult to perform than a simple task with symmetrical lines. We expect to have a model effect due to the shape of the model. The models judged easier will be better performed than the models judged difficult.

Thirdly, the technology takes a long time to get used to and it takes several tries before being able to use correctly. It is therefore expected to observe a learning effect (Farzeeha et al., 2017; Chaniaud et al., 2023; Fleury, Dupont, et al., 2022), giving the user time to find sketching strategies. Users will be more efficient on their third try than on their first try despite the time needed to adapt to the tool.

Fourthly, according to Yang and Lee (2020), Chaniaud et al. (2023) and Barrera Machuca et al. (2019), motion and spatial inspection could also play a crucial role in the creation of a clean design because it allows the user to become aware of 3D. Some do it naturally (Chaniaud et al., 2023), others seem to need to be encouraged to do it. No study to our knowledge has shown the impact of forcing users to move or remain static. We believe that those who are forced to move during the VR sketching task will produce better-quality sketches than those who are forced to remain static.

2 Methods

2.1 Participants

Thirty participants, 15 females and 15 males aged 18–66 years (mean = 34.13 ± 13.75) participated in this study. Anyone who might be able to use this type of software, particularly in a Do-it-yourself or Do-it-together context, was included in the study. All the participants were native French speakers and signed an informed consent form. The data collected about participants was anonymous. This study was in line with the ethical recommendations of the Declaration of Helsinki. Participants did not receive financial compensation. The VR experts were recruited from a center of research in VR and the VR novices were recruited through a call for participation.

2.2 *Materials and measurements*

2.2.1 Time2Sketch *software*

Time2Sketch is an immersive sketching software prototype used in the experiment to allow the user to draw freehand lines in VR. Users have three control buttons. Button A turns on the menu (Figure 1). The trigger on the back allows users to select menu items if the menu is open and to paint/draw if the menu is closed. In the menu, users can change colour and brush size, erase lines, undo the last action, resize the sketch and position a symmetry axis. Finally, the B button on the controller allows users to teleport in the VR environment. The controls are visible to the user. The VR headsets used were Oculus Quest 2. Participants were equipped with both controllers (right and left) even though only one is sufficient for the task. The experimenter was responsible for setting up the participants in the Time2Sketch software.

2.3 *Measure of position and movement*

The headset records the following participants' movements while using the equipment: position in the scene on an x, y, z axis which allows the deduction of the horizontal and vertical displacement of the user (in meters) and headset rotation (yaw, pitch, and roll).

2.4 *Questionnaires*

Five questionnaires were distributed to participants: socio-demographic, traditional drawing skills, VR skills, mental rotation test, and usability questionnaire.

1. Socio-demographic

This questionnaire included personal details of age and gender.

2. Traditional drawing skills

To assess their drawing skills, we asked the participants the following questions: did they have any training in traditional drawing (hobby or professional); how often did they use drawing (never, few, sometimes, often, very often); to evaluate themselves subjectively on their drawing skills, that is, their comfort in drawing (not at all comfortable, a little comfortable, moderately comfortable, quite comfortable, completely comfortable).

3. VR sketching skills: VR expert vs VR novice

To assess their VR skills, we asked the participants the following questions: did they have any training in virtual reality (yes: VR expert, no: VR novice).

Figure 1 Screenshot of the time2sketch software menu

All the VR experts had already used VR sketching and all the VR novices had never used VR sketching.

4. Mental Rotation Test A (MRTA)

The MRTA (by Peters et al., 1995) is a redrawn version of Vandenberg and Kuse's (1978). The test has 24 items organized in four pages. Each item is composed of five figures: a reference model on the left side and four figures located on the right, among which the participants have to indicate the ones that are similar to the reference model. There are always two correct answers per item. The time is divided into 2 × 3 minutes with a 4-min break in between. One point is given per item if the participant finds the two correct figures. No points are given if the participant finds 1 or 0 figures. The sum of these points will give the MRTA score ranging from 0 to 24.

5. System Usability Scale (SUS)

This ten-item survey aimed at recording subjective assessments of usability (Brooke, 1996; Lewis & Sauro, 2009) is a "quick and dirty" tool with five response options from strongly agree to strongly disagree. We used the French-validated version (Gronier & Baudet, 2021). The SUS score ranges from 0 to 100. The closer the score is to 100, the better the perceived usability.

2.5 Procedure

The average duration of this experiment was around 45 min and was structured in four steps: (1) participants were asked to complete a series of questionnaires (socio-demographic, traditional drawing skills, VR skills, MRTA) for 10 min; (2) participants were immersed in a neutral virtual environment (hangar) and were trained to use *Time2Sketch*. There was no time limit to learn the software but they took an average of 10 min to feel comfortable. To validate this step, we asked to the participants to sketch a coffee table. Once they were familiar with the software, (3) Participants were tasked with creating sketches of three chairs consecutively using the Time2sketch software, each associated with a model while carefully controlling for counterbalancing. They were allotted a time frame of 7 min for each sketch, totalling 21 min for the three sketches. The photos of the chairs to be reconstructed in 3D appeared in the immersive environment and remained visible for the duration of the task (see Figure 2). They were asked to reproduce as closely as possible the picture presented in the VR environment. The instructions imposed were always the same: "reproduce the piece of furniture as faithfully as possible, taking into account the volumes and with true-to-scale." These three tasks were associated with three controlled movement conditions ("control", "static", "mobile"), which were also counterbalanced. In the static condition, participants were forced to" stay motionless. They could squat or stand but could not walk in space. In the mobile condition, participants could move as much as they wanted and the examiner insisted that they move by walking around their sketch every 2 min, asking for a total of three rounds. In the control condition, the participants had no constraints. To sum up, the term "condition" refers to the movement conditions: control, static and mobile; the term "model" refers to the three different reference sketches (i.e., three different models of chairs); and the term "session" refers to the rank of the three models performed to study the training effect. (4) Finally, the participants were asked to answer the SUS questionnaire.

2.6 Models

The three models are presented in Figure 3 and were selected according to their complexity. Model 1 includes diagonal lines and important volumes which requires depth in the drawing. Model 2 requires the use of circular lines. Model 3 is considered a simple geometric task with straight lines.

2.7 Measuring quality of the sketches

Two experts in VR drawing independently evaluated each sketch (VR sketches are presented under all faces via a software viewer) with a set of criteria using a

Figure 2 Participant inside the virtual environment sketching Model 2

Figure 3 Presentation of the three original sketches copy models. Model 1, Model 2, and Model 3 are copied using Time2sketch *software in a virtual reality environment*

grid detailing each point of each criterion (Appendix 1): respect for volume; respect for proportion; quality of the lines; fidelity with the original picture. Each criterion is scored from 1 to 5. The sum of the points gives a score between 4 and 20; the higher the score the better the quality of the sketch.

2.8 Data analysis

Results were analysed using SPSS® version 22 (IBM Corporation, 2013). Bivariate correlations and ANOVAs (within subject and between subject) were performed when the sample met the homoscedasticity criteria.

2.9 Inter-judge reliability

We used Intra-Class Correlation (ICC) two-way random to verify inter-judge reliability for the quality of the sketches (Shrout & Fleiss, 1979). The mean ICC measurement for all the tasks was 0.741 with 95 % confidence interval of 0.63−00.822 ($F(88,88) = 6.717$, $p < 0.001$) for the volume, 0.72 with 95 % confidence interval of 0.603−00.807 ($F(88,88) = 6.155$, $p < 0.001$) for the proportion, 0.641 with 95 % confidence interval of 0.501−00.749 ($F(88,88) = 4.575$, $p < 0.001$) for the quality of the line and 0.755 with 95 % confidence interval of 0.65−00.788 ($F(88,88) = 10.712$, $p < 0.001$) for the fidelity. The mean ICC measurement for the total score of the four criteria was 0.844 with a 95 % confidence interval of 0.772−00.894 ($F(88,88) = 11.791$, $p < 0.001$). All criteria above 0.7 are considered good and those above 0.5 as moderate (Koo & Li, 2016). The reliability has been evaluated by a "single rating" which is why we used the data of Judge 1 for the results. The scores of the two judges are presented in Appendix 2.

3 Results

Participant 22's Model 2 scores are missing due to a computer crash when recording the sketch. Data from the other tasks were not removed. Table 1 shows the details of the user characteristics according to the quality score of the sketches for the three tasks. Figure 4 shows some examples of sketches created by the participants. The details of the quality score of the sketches given by the two judges are presented in Appendix 2. All data, appendix and questionnaires used are available in open access on OSF: www.osf.fr.

3.1 Mental rotation skill

Mental rotation skill is positively and moderately correlated (Pearson) with the quality of the three tasks (Task 1: $r = 0.48$, $p = 0.007$; Task 2: $r = 0.51$, $p = 0.004$; Task 3: $r = 0.38$, $p = .04$). The detail of the quality of the sketches according to all the criteria is presented in Table 2 below.

3.2 Shape effect: impact of the models

The models impact significantly the quality of the sketches ($F(2,87) = 3.77$, $p = 0.027$, $\eta^2 = 0.08$), especially Model 3 with Model 1 ($p = 0.025$) and 2 ($p = 0.016$). Model 3 (mean = 12.07, SD = 3.32) obtained better results than Model 1 (mean = 9.83, SD = 3.86) and Model 2 (mean = 9.67, SD = 4.12) which is in line with the second hypothesis.

The models impact significantly the volume ($F(2,86) = 5.92$, $p = 0.004$, $\eta^2 = 0.12$) and the proportion ($F(2,86) = 5.88$, $p = 0.004$, $\eta^2 = 0.12$) but have no impact on the quality of the lines ($F(2,86) = 1.74$, $p = 0.18$) or on fidelity ($F(12,86) = 1.55$, $p = 0.22$). The descriptive analyses are presented in Table 3.

Table 1 Descriptive analyses of user characteristics and user experience in virtual environment and drawing

Variables (N = 31)		*Value (%)*	*Sketching quality score -Model 1 (SD)*	*Sketching quality score -Model 2 (SD)*	*Sketching quality score - Model 3 (SD)*
Participants		30 (100 %)	9.77 (3.91)	9.57 (4.15)	12.03 (3.34)
Age	**Mean**	34.13 years	–	–	–
Gender group (M/F)	**Male**	15 (50)	11.2 (4.06)	11.07 (3.92)	12.13 (3.52)
	Female	15 (50)	8.3 (3.29)	8.07 (3.94)	11.93 (3.26)
Education	**Undergraduate**	2 (6.67)	8.5 (0.71)	8 (2.83)	10.5 (2.1)
	Bachelor degree	11 (36.67)	9.09 (3.96)	8.73 (4.67)	12.09 (3.5)
	Master degree	16 (53.33)	10.44 (4.24)	10.56 (3.93)	12.31 (3.52)
	Technical degree	1 (3.33)	9 (–)	6 (–)	10 (–)
Traditional drawing skills					
Traditional drawing training	**No training in drawing**	19 (63.33)	8.84 (3.4)	9.21 (4.31)	12.26 (3.57)
	Hobbyists drawing training	3 (10)	13.33 (5.85)	12.67 (2.31)	14 (3.6)
	Professional drawing training	8 (26.67)	10.62 (3.89)	9.25 (4.17)	10.75 (2.43)
Frequency of use of the traditional drawing	**Never**	9 (30)	10 (4)	9.67 (4.18)	12.11 (4.34)
	Few	7 (23.33)	8.43 (3.55)	9.14 (5.01)	11.71 (1.6)
	Sometimes	10 (33.33)	10.5 (4.5)	9.9 (3.96)	12.4 (3.83)
	Often	4 (13.33)	9.75 (3.59)	9.25 (4.65)	11.5 (2.65)
	Very often	0 (0)	–	–	–
Comfort in traditional drawing	**Not at all comfortable**	6 (20)	9.5 (4.18)	9 (5.69)	11.33 (2.07)
	A little comfortable	6 (20)	8.83 (2.79)	9 (3.4)	11.17 (2.64)
	Moderately comfortable	9 (30)	9.33 (4.06)	9.11 (4.14)	12.33 (4.5)
	Quite comfortable	9 (30)	11 (4.5)	10.78 (3.93)	12.78 (3.38)
	Completely comfortable	0 (0)	–	–	–
VR drawing skills					
VR skills: Working in virtual reality	**VR experts**	11 (36.67)	11.9 (4.59)	11.36 (3.98)	13.36 (2.5)
	VR novices	19 (63.33)	8.52 (2.91)	8.5 (3.98)	11.26 (3.57)
Mental rotation skills					
MRTA score	**Mean (SD)**	10,70/24 (4.7)	–	–	–
System usability scale					
SUS score	**Mean (SD)**	62.93 (9.03)	–	–	–

3.3 *Training effect: impact of the sessions*

There is a significant impact of the sessions on the quality of the sketches ($F(2,86) = 3.65$, $p = 0.03$, $\eta^2 = 0.08$), especially between Session 1 (mean = 9.27, SD = 3.78) and Session 3 (Mean = 11.79, SD = 3.24, $p = 0.009$) which is in line with the third hypothesis. More precisely, the details of the quality of the sketches according all the criteria is presented on Figure 5. Figure 5 shows the improvement in the four criteria between Session 1, Session 2 and Session 3 on the four criteria. The descriptive analyses are presented in Table 4.

Figure 4 Examples of sketches performed by four participants (5, 8, 16 and 19) according to the three models

Enhancing VR sketching: The role of movement

Table 2 Correlation between MRTA score and the quality of the sketches ($*p < 0.05$, $**p < 0.01$)

Pearson's correlation	*Volume*	*Proportion*	*Quality of the lines*	*Fidelity with the original picture*
Task 1	$r = 0.462*$	$r = 0.41*$	$r = 0.47**$	$r = 0.43*$
N = 30	$p = 0.01$	$p = 0.02$	$p = 0.009$	$p = 0.02$
Task 2	$r = 0.438*$	$r = 0.42*$	$r = 0.38*$	$r = 0.38*$
N = 29	$p = 0.02$	$p = 0.02$	$p = 0.04$	$p = 0.04$
Task 3	$r = 0.34$	$r = 0.31$	$r = 0.32$	$r = 0.39*$
N = 30	$p = 0.06$	$p = 0.09$	$p = 0.08$	$p = 0.03$

The results of Tasks 1 and 2 are in line with our first hypothesis: MRTA scores are significantly correlated to the quality of the sketches for Tasks 1 and 2.

Table 3 Descriptive analyses of ranking of the three models according to the criteria on the quality of the sketches

Models	*Volume*	*Proportion*	*Quality of the lines*	*Fidelity with the original picture*
Model 1	Mean = 2.8	Mean = 2.3	Mean = 2.4	Mean = 2.3
N = 30	SD = 1.16	SD = 0.99	SD = 0.97	SD = 1.05
Model 2	Mean = 3.07	Mean = 2.31	Mean = 2.66	Mean = 1.97
N = 29	SD = 1.13	SD = 1	SD = 1.01	SD = 0.86
Model 3	Mean = 3.73	Mean = 3.07	Mean = 2.87	Mean = 2.4
N = 30	SD = 0.94	SD = 0.98	SD = 0.68	SD = 1.04

The sessions have no impact on the movement of the participants (Horizontal movement: $F(2,86) = 0.721$, $p = 0.49$; Vertical movement: $F(2,86) = 0.794$, $p = 0.45$).

3.4 Motion and spatial inspection: impact of the conditions

3.4.1 Analyses with the experimental conditions ("control", "static" and "mobile")

There is no significant effect of the condition ("control": mean = 11.6, SD = 4.45; "static": mean = 7.64, SD = 3.6; "mobile": mean = 10.56, SD = 2.07) on the quality of the three tasks ($F(2,86) = 0.947$, $p = 0.39$, volume: $F(2,86) = 0.742$, $p = 0.48$; proportions: $F(2,86) = 0.71$, $p = 0.5$; quality of the lines: $F(2,86) = 0.53$, $p = 0.59$; fidelity: $F(2,86) = 1.77$, $p = 0.18$) which is not in line with the fourth hypothesis. However, more precisely, if we analyze Models 1, 2 and 3 separately, we observe a significant impact of the conditions on the quality of the VR sketches of Model 1 ($F(2,27) = 3.54$, $p = 0.04$, $\eta^2 = 0.21$). There are no significant impact of the condition on the quality of Model 2 sketches ($F(2,27) = 0.79$, $p = 0.46$) and on the Model 3 ($F(2,27) = 0.107$, $p = 0.89$). The descriptive analyses are presented in Table 5.

Figure 6 shows mean and standard deviation for volume (mean = 3, SD = 1.17), proportions (mean = 2.4; SD = 0.97), fidelity (mean = 2,

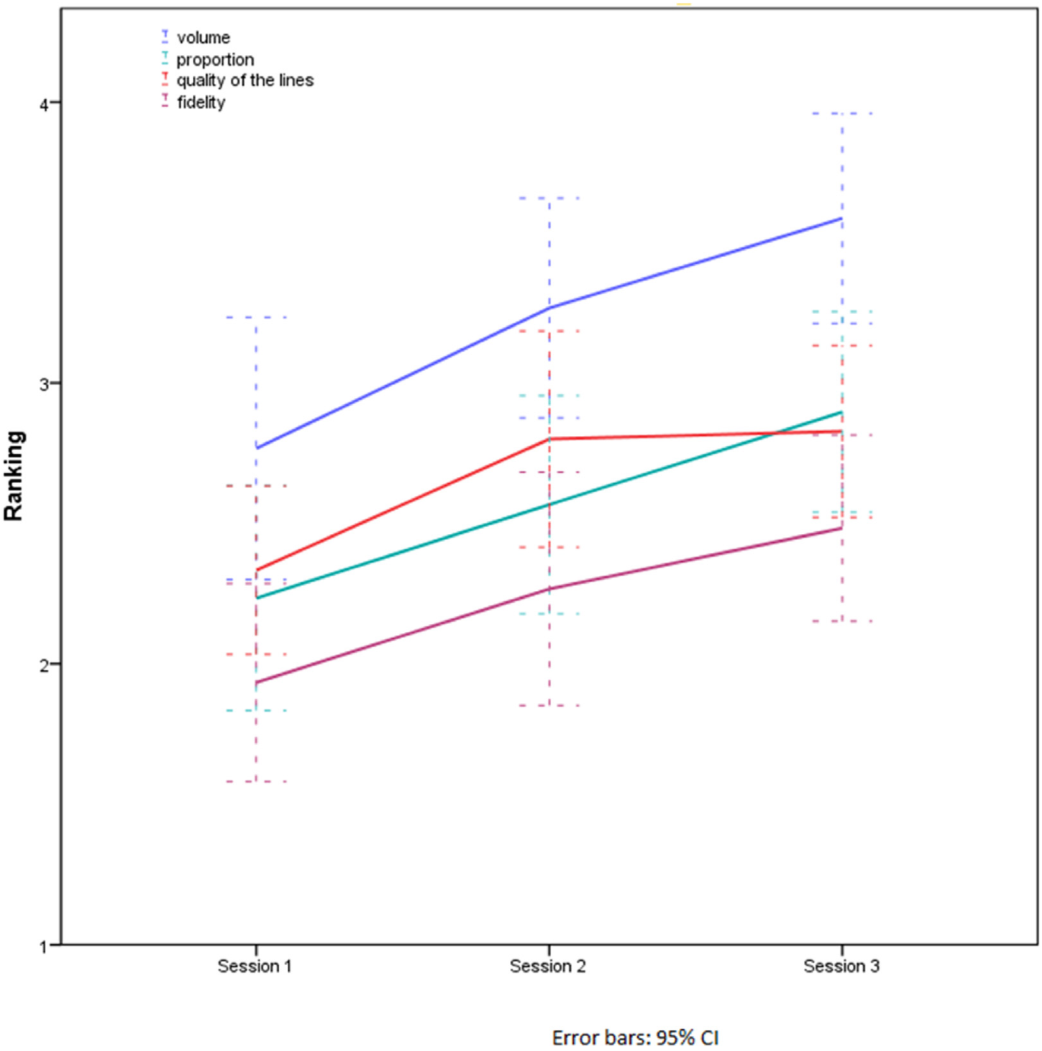

Figure 5 Impact of the session score on the quality of the sketches according to the all criteria

SD = 0.98) and quality of the line (mean = 2.6, SD = 0.93) for the three experimental conditions (“control”, “static” and “mobile”).

3.4.2 Analyses with the headset trackers

The headset trackers recorded significantly more movement in the “mobile” (Horizontal movement: mean = 75.48, meter, SD = 22.79; Vertical movement: 48.02 m, SD = 15.53) and “control” (Horizontal movement: mean = 71.61 m, SD = 31.74; Vertical movement: 47.7 m, SD = 27,1) conditions than in the “static” (Horizontal movement: 52.68 m, SD = 25.63; Vertical movement: 33.92 m, SD = 18.86) condition (Horizontal movement: $F(2, 86) = 6.145$, $p = 0.003$, $\eta^2 = 00.12$; Vertical movement: $F(2,86) = 4.405$, $p = 0.015$,

Table 4 Descriptive analyses of the session score on the quality of the sketches according to the all criteria (*$p < 0.05$)

Models	*Volume*	*Proportion*	*Quality of the lines*	*Fidelity with the original picture*
Session 1	Mean = 2.77	Mean = 2.23	Mean = 2.33	Mean = 1.93
N = 30	SD = 1.25	SD = 1.07	SD = 0.8	SD = 0.94
Session 2	Mean = 3.27	Mean = 2.57	Mean = 2.8	Mean = 2.27
N = 30	SD = 1.05	SD = 1.04	SD = 1.03	SD = 1.11
Session 3	Mean = 3.59	Mean = 2.9	Mean = 2.83	Mean = 2.48
N = 29	SD = 0.98	SD = 0.94	SD = 0.8	SD = 0.87
	$F(2,86) = 4.16$,	$F(2,86) = 3.12$	$F(2,86) = 2.92$	$F(2,86) = 2.35$
	$p = 0.019$*	$p = 0.05$*	$p = 0.06$	$p = 0.1$
	$\eta^2 = 0.09$	$\eta^2 = 0.07$		

Table 5 Descriptive analyses of ranking of the three models according to the conditions (control, static and mobile)

Models	*Control*	*Static*	*Mobile*
Model 1	Mean = 10.44	Mean = 7.54	Mean = 11.6
N = 30	SD = 2.18	SD = 3.67	SD = 4.45
Model 2	Mean = 9	Mean = 11.1	Mean = 8.7
N = 30	SD = 4.5	SD = 3.15	SD = 4.5
Model 3	Mean = 12	Mean = 11.75	Mean = 12.36
N = 29	SD = 3.7	SD = 3.1	SD = 3.36

$\eta^2 = 0.09$). The headset trackers did not record significantly more movement of the head rotation (Yaw: $F(2,86) = 1.92$, $p = 0.15$; Pitch: $F(2,86) = 1.17$, $p = 0.31$; Roll: $F(2,86) = 3.6$, $p = 0.03$).

All the movements recorded are positively and moderately correlated (Pearson) with the quality of the sketches (Horizontal movement: $r = 0.31$, $p = 0.004$; Vertical movement: $r = 0.31$, $p = 003$, Pitch head: $r = 0.39$, $p < 0.001$, Roll head: $r = 0.32$, $p = 0.002$), except for Yaw head rotation ($r = 0.08$, $p = 0.45$), which is in line with the fourth hypothesis. The detail of the quality of the sketches according all the criteria is presented on Table 6 below.

3.5 System Usability Scale

There is no significant correlation between the SUS score and the quality of the sketches (Task 1: $r = -0.06$, $p = 0.7$; Task 2: $r = -0.18$, $p = 0.33$; Task 3: $r = -0.05$, $p = 0.78$).

4 Discussion

The aim of this study was to suggest ways to improve the quality of sketching in VR. To do this, the participants were asked to reproduce three models in three controlled counterbalanced conditions (static, mobile and control). We also collected mental rotation levels using the MRTA, movement with headset

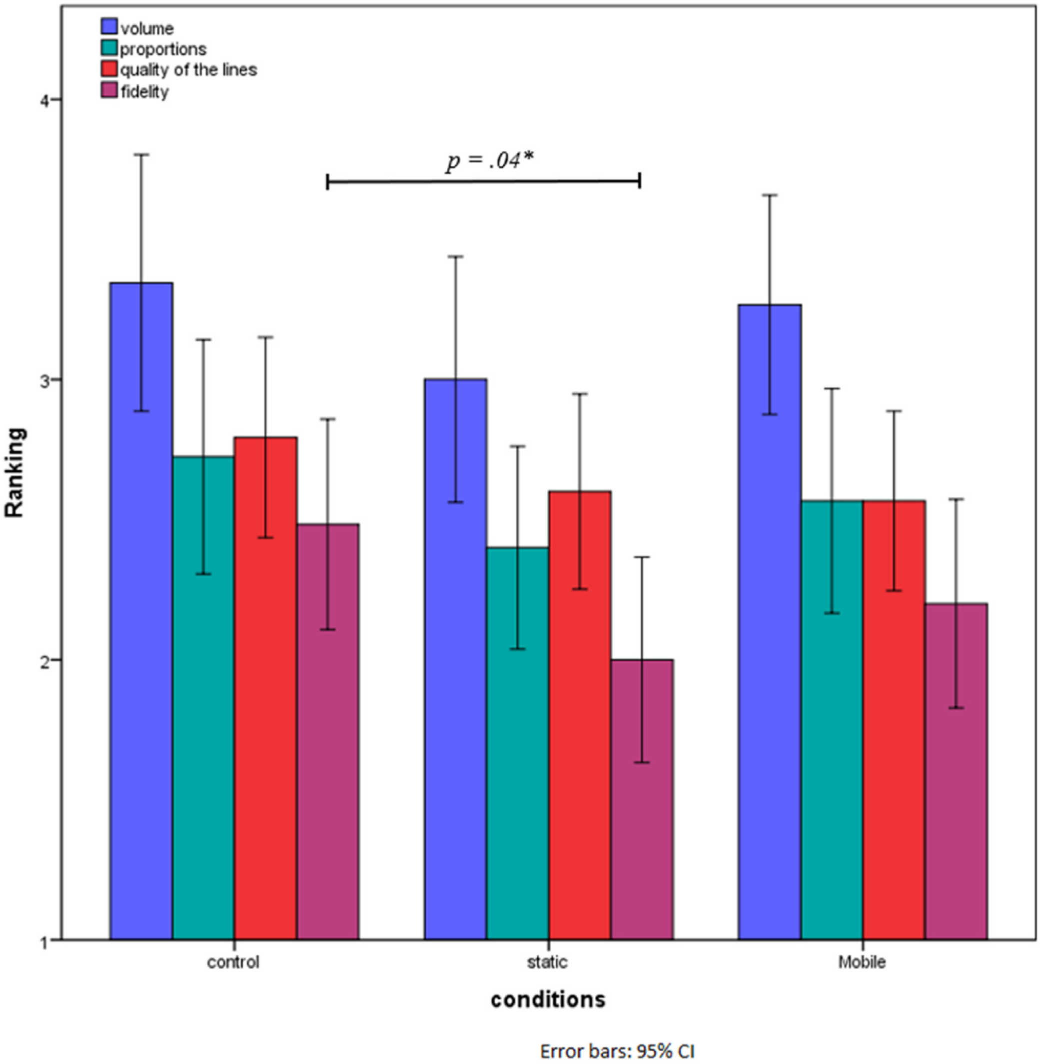

Figure 6 Impact of the conditions (control, static and mobile) according to all criteria on the quality of the sketches (*p $<$ .05*)*

trackers, and two independent judges rated the quality of VR sketches of the participants using four criteria (volume, proportion, quality of the lines and fidelity). We made four hypotheses proposing that mental rotation, training, movement and models would have an impact on the quality of VR sketches.

Our first hypothesis was that the higher the visuospatial abilities of the participant, the higher the quality of the VR sketches. We focused on mental rotation level to assess the visuospatial abilities using the MRTA (Vandenberg & Kuse, 1978). Results validate our hypothesis. A high mental rotation score is related to high quality of VR sketches for all three tasks. These results are partially in line with Barrera Machuca et al. (2019) who found that the user's

Table 6 **Correlation between movement and quality of the sketches ($*p < 0.05$, $**p < 0.01$, $***p < 0.001$)**

Pearson's correlation	*Volume*	*Proportion*	*Quality of the lines*	*Fidelity with the original picture*
Horizontal movement	$r = 0.3**$ $p = 0.004$	$r = 0.33**$ $p = 0.001$	$r = 0.19$ $p = 0.08$	$r = 0.29**$ $p = 0.006$
Vertical movement	$r = 0.3**$ $p = 0.005$	$r = 0.36***$ $p < 0.001$	$r = 0.18$ $p = 0.09$	$r = 0.29*$ $p = 0.005$
Yaw head	$r = 0.002$ $p = 0.99$	$r = 0.12$ $p = 0.26$	$r = 0.05$ $p = 0.62$	$r = 0.13$ $p = 0.24$
Pitch head	$r = 0.35***$ $p < 0.001$	$r = 0.36***$ $p < 0.001$	$r = 0.36***$ $p < 0.001$	$r = 0.34***$ $p < 0.001$
Roll head	$r = 0.31**$ $p = 0.003$	$r = 0.3**$ $p = 0.005$	$r = 0.29**$ $p = 0.005$	$r = 0.26*$ $p = 0.01$

visuospatial abilities – using the vz-2 paper folding test (Ekstrom, French, & Harmon, 1976) and the perspective taking/spatial orientation test (Kozhevnikov & Hegarty, 2001) – affects the shape of the sketches, but not the line precision in the VR sketching. In our case, mental rotation impacts all the criteria with the exception of the volume, proportion and quality of the lines of Model 3. Most participants reported that Model 3 was the easiest. We replicated the results of Chaniaud et al. (2023). The authors analyzed two different sketching models in terms of complexity. Mental rotation impacted the quality of both models. Unlike Chaniaud et al. (2023), our models (chairs) had fewer complexity gaps and were radically different compared to their models (shelf and cupboard). We used three distinct models of the same item of furniture (a chair); the level of complexity did not vary much but each may require different drawing strategies. If Model 3 was judged easier, we still expected to have an impact of the quality of the drawing according to the MRTA score. It is probably because the task requires less visual-spatial ability. Further studies are needed to ensure that mental rotation is a required ability to create virtual reality sketching.

Our second hypothesis potentially explains the results of the first hypothesis, that is, there is an impact from the models. We suggested that Model 3 would be the easiest because of the straight and symmetrical lines and included few details compared to the two other models and Model 2 would be the most difficult because of the curve lines. Our result validates our hypothesis.

Our third hypothesis was that users would be more successful in their third session than in the first despite the time needed to adapt to the tool. We analyzed the order of the tasks independently of the models and the conditions. Results validate our hypothesis. We observed that the first session was significantly lower rated than third, which means that there was a training effect. All the rating criteria are better rated in the third session except for the quality of the lines which seems to stabilize (Figure 5). Our results are in line with those of Fleury, Dupont, et al. (2022) who present results from a focus group where participants felt more comfortable sketching in VR after some practice. This suggests that it is possible to make progress after several sessions. It would therefore be appropriate to ask users to perform several different sketching tasks before making their final sketch. Our results could also agree with those of Gómez-Tone, Martin-Gutierrez et al. (2021) who show that users improve their mental rotation skill after regular use of VR sketching but it is unclear whether this is due to a training effect or an improvement in visuospatial skills.

The fourth hypothesis was that participants who were forced to move during the VR sketching task would produce better quality sketches than those who were forced to remain static. There were two ways to collect the data: with the conditions ("mobile", "static" and "control") and with the headset recordings. Results partially validate our hypothesis. First, the participants forced to be static produced sketches of lesser quality than the mobile condition. In contrast, the mobile condition was no better than the control condition, which means that users did not improve their sketches by moving since they seemed to move naturally in the control condition. This implies that the static condition has worsened the quality of the sketches. In addition, participants, frustrated by not being able to move, told us that they used strategies to make their sketches move by grabbing it and twisting it around. After analysis of the headset trackers, we could observe that the control and mobile conditions moved as much, and significantly more than the static condition. Second, the headset recordings show moderate and significant positive correlations between movement (of the body and head rotation) and sketch quality, which is in line with the results of Chaniaud et al. (2023). This means that using more movement produced a better-quality sketch, especially for the volume and proportion (see Table 6). Indeed, movements allow a better depth perception (Arora et al., 2017; Cave & Kosslyn, 1993; Tramper & Gielen, 2011) which allows a better spatial representation (Cave & Kosslyn, 1993). The recorded head rotations, especially roll and pitch rotations probably allowed the static group to compensate somewhat for their lack of body movement but it was not enough to perform as well as the mobile or control conditions. The user must be able to step back sufficiently. Thus, the static group was disturbed in their depth perception.

According to Yang and Lee (2020), movement and spatial inspection may be the key to the success of a sketch, especially for those who already move naturally (Chaniaud et al., 2023). Nevertheless, forcing users to move (even those who are novice or who have poor mental rotation skill) did not improve their sketches as expected. Participants may have been disturbed by being interrupted every 2 min to take the time to move around, which could explain why the mobile condition did not perform better than the control condition. It may not be possible to improve the user's perception using movement, as depth perception may be an intrinsically embedded skill. Cornilleau-Pérès and Gielen

(1996) use the term "self-motion" to describe this natural effect of moving in order to perceive 3D. Visual perception of 3D space, based on various cues including motion parallax, binocular disparity and coupling between head movements and visual inputs, is involved in most aspects of self-motion perception and control. The authors explain that "an observer standing in front of a frontoparallel stationary plane develops a spontaneous postural sway" (Cornilleau-Pérès & Gielen, 1996, p. 197). This suggests that self-motion is a prerequisite for 3D perception, but can be more or less developed depending on the subject.

The results also showed the perceived usability (measuring with the SUS) is not correlated with the quality of the sketches, which means that the software was not considered more difficult for those with lower quality sketches. This suggests that there is no tool-specific difficulty that would explain the variability in sketching performance. Nevertheless, the average SUS score was 62.93, which is "marginal" (Brooke, 1996) and implies that improvements could be made on the software. It has been known for a long time that usability is a major factor of technology acceptance (Davis, 1989). Nevertheless, we can question whether this low score is due to the software itself or the difficulty of creating 3D drawings. It would be interesting to conduct this study using other VR drawing software.

How to improve the quality of the sketches? Firstly, neither the model nor the condition impacts the quality of the lines because it aligns with the skills of the users independently of their environment. Training seems to have an effect that can improve the quality of the lines even if this effect seems to stabilize with time. Longitudinal studies should be conducted to better understand how users progress. This would also allow us to know if it is the improvement of mental rotation skills that allows users to draw better or vice versa. Secondly, some guidelines given to users, such as training on several tasks before the main task, can improve the volume and proportion of the sketches and thus the fidelity. Based on our results, we can conclude that movement is the key to successful sketch quality only for those who move naturally. Those who do not move did not change their behavior after being forced to move during the mobile condition. Our observations showed that some users took a while to understand that it was easier to draw while moving. Therefore, participants did not learn to move. This would probably come from their visuospatial skills and their ability to move in a virtual environment. Designers could adapt VR sketching software to optimize 3D visualizations (e.g., encourage users to rotate their sketches). These elements should be investigated in future studies.

4.1 Limitations and perspectives

This study has several limitations and perspectives. Firstly, users reproduced a 2D drawing and had to interpret what it would look like in 3D. Users could draw on their prior knowledge to help them consider the shape of the furniture (Frith & Law, 1995). The presentation of a 3D object to reproduce would be an interesting way to better understand visuospatial functioning during 3D drawing tasks. In addition, the tasks required were to make a copy of an existing design. Therefore, we can assess the participants' drawing skills based on different shapes but not their design abilities. Nevertheless, this preliminary step of understanding drawing quality through replication, along with a rigorous experimental protocol, is essential for comparing the quality of drawings, shapes, and conditions. Future studies on this subject will aim to investigate whether the quality of the sketches is an obstacle to design process or creativity (e.g., Chan & Zhao, 2010) or if, on the contrary, fuzzy shapes might be a new source of inspiration for the users (e.g., Buxton, 2010; Ullman, Wood, & Craig, 1990). For instance, Chan and Zhao (2010) showed in a study with primary, secondary and university students, a correlation between drawing skills and artistic creativity; what about sketching in VR? Secondly, it would be interesting to interview users who do not move much to understand why they do not or observe the movements of a VR sketching expert. Perhaps an exercise of moving around in the environment at the same time as learning the software would allow users to feel more comfortable in the environment, or a motion detection software could warn users if they stayed static too long. In the study by Wang, Miller, Han, DeVeaux, and Bailenson (2024), the authors demonstrate that design behaviors, particularly the consideration of space (i.e., volume), differ when users are alone versus in groups. Consequently, it would be valuable to investigate whether users are more likely to move around when they are in a group compared to when they are alone. Thirdly, improvement on the three tasks seems to continue (Figure 5). It would have been interesting to know how many tasks are required before obtaining a stable and sufficient level for participants to be totally satisfied with their sketches. Finally, this study remains dependent on the software used, the sample including the participants' abilities and the methodological choices for assessing the quality of the drawings.

5 *Conclusion*

To conclude, VR sketching is a complex task: movement, spatial inspection, training, and mental rotation skills are all key to quality sketches. It is strongly advised that users move around in the virtual environment during a VR sketching task to become aware of the depth of the drawing in progress but, above all, the most important thing is not to remain static. We also recommend practising several tasks before performing the main task, especially if the user has poor spatial skills. Designers will also be able to take this data into account to implement design recommendations (such as encouraging users to rotate their drawings) to help with better 3D perception and maximize opportunities for communication and creativity in the design process.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Noémie Chaniaud: Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sylvain Fleury:** Validation, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Benjamin Poussard:** Software, Resources, Project administration, Funding acquisition. **Thibaut Guitter:** Software, Resources, Data curation. **Simon Richir:** Funding acquisition.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.destud.2025.101298.

Data availability

Data will be made available on request.

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