Why does the quality of sketches in virtual reality depend so much on individuals? Analysis and identification of factors based on laboratory and field experiments

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ABSTRACT
Virtual reality (VR) sketching tends to be democratized in the early stages of design for several reasons (e.g., improved creativity). Nevertheless, our field studies and the scientific literature identified some constraints to the use of VR sketching such as the low quality of the sketches impacting the acceptance of the design tool for the future users. The objective of our study is better understand them to improve the quality of user sketches. Thirty-one participants completed questionnaires (VR and drawing experience, visuo-spatial skills, usability) and performed 2 VR sketching tasks. Sketch quality was evaluated using a multifactorial approach (volume, proportion, fidelity). The results showed that each skill (visuo-spatial abilities, drawing experience and spatial inspection) has a specific impact on some factors. We detailed the results and proposed recommendations for improving the use of the sketching software and sketches quality.

Keywords
Usability; User-centered design; Technology acceptance; acceptability; ergonomics; Virtual reality sketching

INTRODUCTION
Drawing and sketching is a powerful way of expressing and communicating concepts especially in ideation phase [1]. In recent years, Virtual Reality (VR) sketching is being increasingly used in the early design phases with designers and with non-designers (end-users) in co-design or participatory design process. This activity let users to draw 3D shapes in a virtual environment using freehand drawing. VR sketching provides exciting alternatives for creating and expressing new design ideas and communicating visually. Users can move around their sketches to see them with different viewpoints. Freehand movements and walking are intuitive and easy to use in virtual environment [2]. Nevertheless, VR sketching seems to be more difficult to use compared to traditional sketching with paper and pencil [e.g. 3], especially, the most common difficulty is the lack of accuracy [4 - 6]. In this paper, we tried to better identify the constraints and then to present the results of an experimental study to understand the cognitive and motor mechanisms underlying these difficulties of use.

In a previous study [7], we observed the process of getting used to the VR sketching software in a natural environment. Three groups of seven students from different fields (business, design, marketing) had to co-create furniture layout for a specific room. To do this, they followed the innovative design process described by Fleury, et al. [8]: brainstorming, 3D scanning of the room and sketching ideas in VR. Participants completed the process twice in two days. Before sketching ideas in VR, all groups systematically made traditional sketches in 2 dimensions (Fig. 1). We observed a significant disparity in the quality

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of the VR sketches among the participants. Users reported feeling much more comfortable with the material on the second day and used different features of the software more than others. These results show that training seems to be an important element to consider for the acceptance of VR sketching software. Furthermore, we conducted focus group interviews (ad hoc) with them about the use of VR sketching at the end of the experiment. Most of them found the VR sketching tasks to be a complex activity. They said that the result was "rough", "it does not make the piece of furniture look realistic", "the fact that it's not clean, I didn't feel immersed". These citations are in line with Arora et al. [4], Wiese et al. [6]. It seems that the major constraint to the acceptance of VR sketching is the lack of accuracy. The objective of this paper is to better understand why this lack of accuracy occurs.

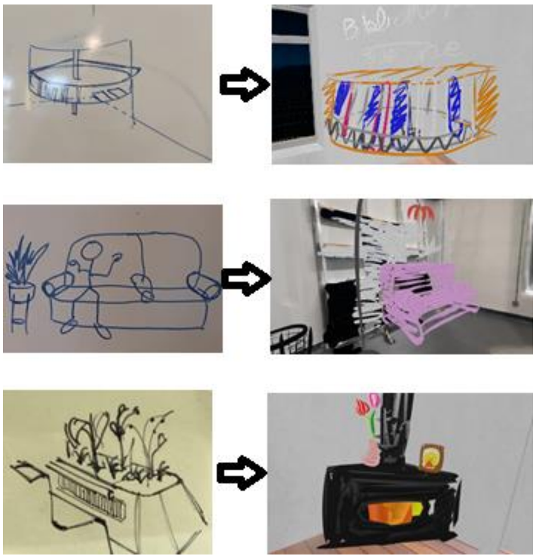

Figure 1. For images, be sure to have a good resolution image (see item D within the preparation instructions).

ACCURACY IN VR SKETCHING

The lack of accuracy is one of the main challenges that VR sketching is facing [3, 4, 6]. Accuracy is detrimental to the creation process because the sketch may not correspond to the user's intention [3]. Why is it so difficult to be accurate in VR sketching? We could identify two main reasons: (1) the tool itself is not that easy to use, (2) the tool requires certain skills that not all users have.

VR sketching has no physical surface unlike traditional sketching with paper and pencil [4]. Therefore, the lines can be rounded instead of straight. The users have no reference point and have to move if they want to observe the curve of the lines. VR sketching requires depth perception which is also a source of error for users [4,9,10]. The lack of depth perception does not allow a correct spatial representation [9]. Thus, VR sketching requires movements and spatial inspection. Yang and Lee [11] highlight that spatial inspection is a behavioural factor for successful VR sketching. Barrera Machuca et al. [3] explain that users need to use different views to plan their next hand movement. All these arguments seem to converge towards the importance of considering the spatial environment and visuo-spatial abilities [e.g., 3,12-14].

Compared to traditional sketching, VR sketching requires higher demands on the user's perceptual, motor, and visuo-spatial abilities [3]. Two factors seem to have a significant impact on the quality of sketches: training and visuo-spatial abilities. Perdreau and Cavanagh [15] et McManus et al. [16] showed that traditional drawing experts have a better visual memory than novices. This would be related to the ability to copy angles and simple proportions [16]. Barrera Machuca et al. [3] found that the user's spatial ability affects the shape of the drawing but not the line precision. In a drawing task, when participants reproduce a simple or complex shape, they have to plan the sequence of elements to be drawn and they have to consider the spatial relationships between them [13]. From this point of view, drawing can be enhanced as a particular type of construction task. This involves developing a strategy and learning how to draw [13]. Moreover, Wiese et al. [6] showed that quality of VR sketches improves over time. These arguments show that drawing training could have an impact on several elements of the quality of sketches including proportions, shapes, and picture fidelity and that the visuo-spatial abilities would have an impact on the shape but not necessarily on the details. Nevertheless, these arguments have never been demonstrated experimentally.

To sum up, we identified four factors that can impact the quality and accuracy of sketches in VR: drawing and VR experience, visuo-spatial abilities. movement and spatial inspection, and software usability. Nevertheless, we do not know how those factors impact the quality (volume, proportions, fidelity). The objective of this study is to better understand the impact of these factors according to the three quality criteria. We formulated four hypotheses:

Firstly, we hypothesize that the experience has an impact on the all the criteria of the quality of a sketch (volume, proportions, and the picture fidelity). Users who have VR or drawing experience will produce sketches with a better volume, better proportions, and will be more faithful to the original picture.

Secondly, we hypothesize that visuo-spatial abilities have an impact on the volume but not necessarily on the picture fidelity. Participants with high visual-spatial skills will produce sketches with better volume.

Thirdly, we hypothesize that movement and spatial inspection impact the volume. Participants who move the most will produce sketches with a better volume.

Fourthly, usability of the software impact all the criteria. The easier the software is judged to be to use, the better the quality of the sketches will be.

METHOD

Population

Thirty-one participants, 15 females and 16 males aged 18-62 years (means = 34.03 ± 12.75) participated in this study. All the participants were native French speakers and signed an informed consent form. The data collected on 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 (VR experience) were recruited in a center of research in VR and the VR novices (no VR experience) were recruited through a call for studies.

Procedure

The experiment was structured in 3 steps: (1) participants were asked to complete a series of questionnaires (socio-demographic, drawing experience, VR skills and mental rotation test); (2) then the participants were immersed in a neutral virtual environment (hangar) and were trained to use a VR sketching software named Time2sketch. There was no time limit for them to learn the software. Once they were familiar with the software, they had to perform the sketching tasks in virtual environment. The photos of the pieces of furniture (Fig. 2) to be reproduced in 3D appeared in the immersive environment. The two VR sketching tasks were presented randomly and consecutively to the participants. Participant had 10 min to make the basic task (the shelf – task 1) and 20 minutes for the complex task (the buffet – task 2). The instructions imposed were always the same: "reproduce the furniture as faithfully as possible, taking into account the volumes". These two pieces of furniture have been selected according to their complexity. The shelf (task 2) is a simple task with a simple geometric shape, while the buffet is a complex task requiring to take into account the opening angle of the cabinets and drawers and many details. (3) Finally, the participants were asked to answer the SUS questionnaire.

Figure 2. Presentation of the two drawing copy tasks. The basic task 1 (the shelf) and the complex task 2 (the buffet) are copied using Time2sketch software in a virtual environment.

Material and measurements

Time2sketch software

Time2Sketch is an immersive sketching software used in the experiment to allow the user to draw freehand lines in VR. Users can change colour, brush size, erase the lines, undo the last action, resize the sketch and teleport in the environment. The VR headsets used was Oculus Quest.

Questionnaires

Five questionnaires were distributed to participants: (1) socio-demographic, (2) drawing experience, (3) VR skills, (4) Mental Rotation Test A, and (5) usability questionnaires.

- The socio-demographic questionnaire included personal details: age and gender.
- To assess the drawing experience, we asked the participants the following question: did they have any training in traditional drawing (hobby or professional). They could answer yes or no.
- To assess the VR skills, we asked the participants the following questions: did they have any training in virtual reality (yes: VR expert, no: VR novice): did they have ever used VR sketching (yes, no). All the VR experts have already used VR sketching and all the VR novices have never used VR sketching.
- The MRTA [17] is a redrawn version of Vandenberg and Kuse [18]. The test has twenty-four items organized in 4 pages. Each item is composed of 5 figures: a reference model on the left side and 4 figures located to the right side of the reference model 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 2x3 minutes with a 4-minute 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 MRT score ranging from 0 to 24
- To assess the usability questionnaire, we used the System Usability Scale (SUS) which is a 10-item self-report survey, "quick and dirty" tool with five response options from strongly agree to strongly disagree [19,20]. We used the French validated version [21].

Measure of position and movement

The headset records the position in the scene on an x, y, z axis which allows to deduce the horizontal and vertical displacement of the user (in meters) while using the equipment.

Measure quality of the sketches

Two expert judges evaluated independently each sketch (VR sketches are presented under 4 faces: top, profile, front and ¾ frontal – see Fig. 3) with a set of criteria:

- Respect for volume: The overall shape of the piece of furniture must be three-dimensional and have depth. The main angles of the furniture must follow 90°. The lines must be at least straight.

- Respect for proportions: Balance of surfaces, masses, dimensions (example: for the buffet, the size of the upper levels must be smaller than the lower ones).
- Fidelity with the original picture: final aesthetics, integration of elements to make the picture more realistic, taking into account details (example: opening of drawers and shelves).
- Each criterion is scored 0 to 1. The sum of the points gives a score between 0 and 3. The higher the score the better the quality of the sketch.

Data analysis

Results were analyzed using SPSS® version 22 (IBM Corporation, 2013). Each score task was systematically compared to user characteristics and usability components. Bivariate correlations and ANOVAs were performed when the sample met the homoscedasticity criteria.

Inter-judge reliability

We used Intra-Class Correlation (ICC) to verify inter-judge reliability for the quality of the sketches [22]. The mean ICC measurement for the task 1 (the shelf) was .95 with 95% confidence interval of .897 to .976 ($F(30,30) = 20.2$, $p < .001$) for the volume, .88 with 95% confidence interval of .763 to .945 ($F(30,30) = 8.739$, $p < .001$) for the proportions, .88 with 95% confidence interval of .755 to .943 ($F(30,30) = 8.467$, $p < .001$) for the fidelity. The mean ICC measurement for the task 2 (the buffet) was .943 with a 95% confidence interval of .883 to .973 ($F(30,30) =17.667$, $p <.001$) for the volume, .855 with 95% confidence interval of .699 to .93 ($F(30,30) = 6.9$, $p < .001$) for the proportion, .687 with 95% confidence interval of .35 to .849 ($F(30,30) = 3.194$, $p < .001$) for the fidelity. For the results section, we used only the data from judge 1.

RESULTS

Figure 3 shown some examples of sketches created by the participants. Participants 1, 11, 15, 30 have no training in traditional drawing compare to participants 5 and 7. Participants 1, 11, 30 have no experience in VR compare to participants 5, 7, 15 who are considered VR experts. If the average MRT score is considered to be 12, then participants 1, 5, 7 are above average and participants 11, 15, 30 are below average.

Descriptive analysis

The mean score for task 1 is 1.22/3 (SD = 0.845) and the mean score for task 2 is 1.45/3 (SD = 0.92).

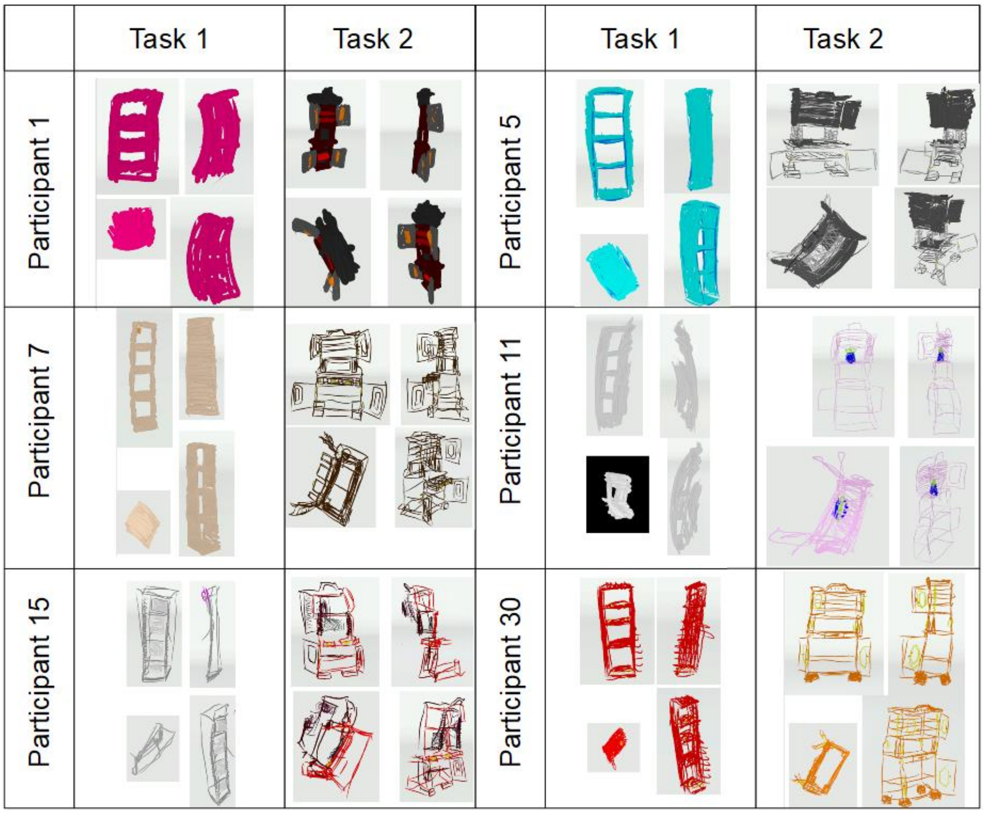

Figure 3. Examples of the quality variety of sketches.

Respect for volume

Except the MRT score (Mann-Whitney U = 147.5, p = .001), all the factors have no significant impact on the volume for the task 1 (VR experience : F(1,29) = 1.92, p = .18 ; drawing experience : Mann-Whitney U = 105, p = .341 ; SUS score : F(1,29) = 1.55, p = .22 ; horizontal movement : F(1,29) =0.44, p = .51, vertical movement : F(1,29) = 0.12, p = .73).

Except the movement (horizontal movement : Mann-Whitney U = 132, p = .003, vertical movement : Mann-Whitney U = 137, p < .001), all the factors have no significant impact on the volume for the task 2 (VR experience : F(1,29) = 0.96, p = .33 ; drawing experience : Mann-Whitney U = 93, p = .39 ; MRT score : F(1,29) = 1.91, p = .18 ; SUS score : Mann-Whitney U = 101, p = .21). The descriptive results on the respect of the proportion are detailed in table 1.

Table 1. Respect for volume.

Factors	**Task 1 – Volume respected (means – SD) N = 24**	**Task 1 – volume not respected N = 7**	**Task 2 – volume respected (means – SD) N = 25**	**Task 2 – volume not respected (means – SD) N = 6**
MRT score	12.21 (4.78)	6.14 (2.27)	11.44 (4.92)	8.33 (5.09)
SUS Score	77.08 (11.58)	70.36 (15.77)	77.3 (10.73)	68.33 (18.28)
VR experience	0.58 (0.5)	0.29 (49)	0.56 (0.51)	0.33 (0.52)
Drawing experience	1.33 (0.64)	1 (0)	1.32 (0.63)	1 (0)
Spatial inspection (horizontal and vertical movement)	Horizontal: 90.83 (39.59) Vertical: 58.68 (27.19)	Horizontal: 79.66 (37.69) Vertical: 54.63 (26.96)	Horizontal: 225.82 (78.11) Vertical: 147.15 (49.9)	Horizontal: 121.38 (46.21) Vertical: 72.25 (26.86)

Respect for proportions

The MRT score (F(1,29) = 7.57, p = .01, χ = 0.21) and VR experience (F(1,29) = 4.65, p = .04, χ = 0.14) impact the proportions of the sketches. But the SUS score (F(1,29) = 0.003, p = .96), the drawing experience (Mann-Whitney U = 156.5, p = .085) and the horizontal (Mann-Whitney U = 102, p = .65) and vertical (Mann-Whitney U = 93, p = .42) movements have no impact on the proportions of the sketches for the task 1.

The MRT score (F(1,29) = 5.88, p = .022, χ = 0.17), VR experience (F(1,29) = 6.24, p = .018, χ = 0.18), and horizontal (F(1,29) = 6.78, p = .014, χ = 0.19) and vertical (F(1,29) = 6.33, p = .018, χ = 0.18) movements impact the proportions of the sketches. Conversely, drawing experience (Mann-Whitney U = 168, p = .06) and the SUS score (Mann-Whitney U = 130.5, p = .68) have no impact on the proportions of the sketches for the task 2.

The descriptive results on the respect of the proportion are detailed in table 2.

Table 2. Respect for proportions.

Factors	**Task 1 – Proportionate sketches (means – SD) N = 12**	**Task 1 – not proportionate sketches N = 19**	**Task 2 – Proportionate sketches N = 15**	**Task 2 – not proportionate sketches N = 16**
MRT score	13.67 (4.23)	9.05 (4.73)	12.93 (5.09)	8.88 (4.21)
SUS Score	75.42 (9.64)	75.66 (14.53)	76.33 (9.9)	74.84 (15.12)
VR experience	0.75 (0.45)	0.37 (0.49)	0.73 (0.46)	0.31 (0.5)
Drawing experience	1.58 (0.79)	1.05 (0.23)	1.53 (0.74)	1 (0)
Spatial inspection (horizontal and vertical movements)	Horizontal: 86.59 (36.62) Vertical: 54.15 (25.43)	Horizontal: 89.39 (41.12) Vertical: 60.05 (27.97)	Horizontal: 242.6 (74.88) Vertical: 156.3 (47.08)	Horizontal: 170.94 (78.16) Vertical: 110,48 (53,8)

Respect for proportions

There are significant impacts of the MRT score (F(1,29) = 5.8, p = .023, χ = 0.17) and drawing experience (Mann-Whitney U = 82,5, p < .001) but there are no significant impacts on the VR experience (Mann-Whitney U = 64.5, p = .14), SUS score (F(1,29) = 0.001, p = .97), and horizontal (F(1,29) = 0.29, p = .59) and vertical (F(1,29) = 0.24, p = .63) movements on the fidelity of the picture of the sketches for the task 1.

There are significant impacts of the MRT score (F(1,29) = 4.094, p = .05, χ = 0.12), VR experience (Mann-Whitney U = 102.5, p = .041), drawing experience (Mann-Whitney U = 114, p = .006), conversely there are no significant impacts of the SUS score (F(1,29) = 0.074, p = .78) and horizontal (F(1,29) = 0.005, p = .94) and vertical (F(1,29) = 0.01, p = .92) movements on the fidelity of the picture of the sketches for the task 2.

The descriptive results on the respect of the proportion are detailed in table 3.

DISCUSSION

The aim of the study is to better understand the variability in VR sketches quality. To do this, we identified four main factors (VR and drawing experiences, visuo-spatial abilities, spatial inspection and movements and usability) from the scientific literature that could have an impact on three main criteria (volume, proportions, fidelity).

Table 3: Fidelity of the picture

Factors	Task 1 – Fidelity of the picture (means – SD) N = 28	Task 1 – non-fidelity of the picture (means – SD) N = 3	Task 2 – Fidelity of the picture (means – SD) N = 5	Task 2 – non-fidelity of the picture (means – SD) N = 26
MRT score	17 (2)	10.18 (4.8)	14.8 (3.35)	10.08 (4.97)
SUS Score	75.83 (6.29)	75.54 (13.25)	77 (5.42)	75.3 (13.7)
VR experience	1 (0)	0.46 (0.51)	1 (0)	0.42 (0.5)
Drawing experience	2.67 (0.58)	1.11 (0.32)	2.2 (0.84)	1.1 (0.27)
Spatial inspection (horizontal and vertical movement)	Horizontal: 76.66 (32.13) Vertical: 50.5 (29.63)	Horizontal: 89.56 (39.78) Vertical: 58.54 (26.89)	Horizontal: 203,19 (76.83) Vertical: 130.41 (50.91)	Horizontal: 206.08 (86.31) Vertical : 133.08 (56.68)

We made four hypotheses regarding the specific impact of these factors on the three dimensions of design quality.

Our first hypothesis was that participants with VR experience or drawing experience will produce sketches with a better volume, better proportions, and will be more faithful to the original picture. Results partially validate our first hypothesis. VR experience has an impact on proportions and drawing experience has an impact on fidelity. Drawing experience would allow to know better the details to consider making a realistic drawing. However, this has no impact on the volume and proportions. These results are not in line with McManus et al. [16]. Their arguments do not seem to apply to VR. Nevertheless, VR experience have mainly an impact on proportions. The proportions may not be related to the visual memory in VR but mainly to the ability to represent the sketch in 3D. This would explain why the VR experience also allows for a more faithful and accurate reproduction of task 2 (complex task).

Our second hypothesis was that the higher the visuo-spatial abilities of the participants, the higher the quality of the VR sketches. We focused on mental rotation to assess the visuo-spatial abilities using the MRT [18]. Results partially validate our hypothesis. A high mental rotation score is related to high quality of volume, proportions, and fidelity of the sketches. Barrera Machuca et al. [3] show that the user's visuo-spatial abilities measured by the vz-2 paper folding test [23] and the spatial orientation test [24] affect the shape of the sketches, but not the line accuracy in VR sketching. Our results are in line with the fact that visuo-spatial abilities impact the volume (especially for simple shape – task 1), but that seems to also impact the line accuracy. Indeed, the lines accuracy can be associated with the fidelity of the picture because this criterion includes the details and the realism including criteria of accuracy.

Our third hypothesis was that movement and spatial inspection impact the volume. Our results partially validate our hypothesis. These results are in line with Yang and Lee [11] and Barera Machuca et al. [3] but it gives more clarity on the importance of the movement in the VR sketching. The movement has an impact on the volume and also on the proportions but only when it is a complex shape. The movement would compensate for the difficulties in the production of complex shapes.

Our fourth hypothesis was that usability of the software impacts all the criteria. Our results invalidate our hypothesis. Usability has no impact on the quality of the sketches (volume, proportions, and fidelity). The mean SUS score was 75.57 (SD = 12.68), which is "satisfactory" [20]. This suggests that participants did not report being bothered by the usability of the software. The software *Time2Sketches* is easy enough to handle for users. The quality of the sketches would thus be exclusively linked to inter-individual factors. Machuca et al., [5] suggest adding different guides (Smart3Dguides) to help users in the accuracy of their feature. Nevertheless, this raises fundamental questions: should the software be made more complex to help users gain precision so that they are more satisfied with their productions? Should we add options (e.g., remove smoothing, add surfaces) in the software?

According to Buxton [25], sketches in a design project must be both quick to make, understandable, and intentionally ambiguous to be effective in the creative process. In addition, low stroke precision is often intentional since it can make a drawing more expressive [26]. Ambiguity would therefore be positive. Users who are either inexperienced with drawing and VR or have poor visual-spatial abilities or remain static when sketching will produce ambiguous VR sketches which may be beneficial for jumping to other ideas. However, it could be detrimental to an efficient communication of ideas. However, innovation is a collective process and needs communication of ideas between participants.

We believe that collaboration could solve this dilemma. We found that three factors impacted the quality of the sketches differently. This implies a degree of complementarity in the profiles to constitute working groups. The integration of various profiles in the working groups would allow a better collaboration and would compensate for the weaknesses of the collaborators. During the previous study [7], we observed the collaboration within the three groups (Fig. 4). Some participants were naturally attracted to VR sketching. Leaders in VR sketching could be identified in all three groups. They were more likely to produce high quality sketches although all tried and presented production. The collaboration made up for the difficulties in getting quality sketching. It could be interesting to create working groups according to skills (visuo-spatial abilities, drawing and VR experiences) to verify this argument and suggest improvements in VR sketching in ideation phase.

Some limitations and perspectives appear with this study: firstly, we used students for the field experiment, which is not representative of a target population, even if it is close. For example, this excludes criteria such as the diversity of profiles related to age. Secondly, to the best of our knowledge, there are no scoring criteria for evaluating drawings in virtual reality. We therefore suggest our own criteria which would deserve to be evaluated on several studies with several judges. Thirdly, other types of 3D virtual reality drawing exist (e.g., Hyve-3D). The Hyve-3D [27] would allow to realize cleaner drawings but would have a longer learning process. It would be interesting to know which tools would be the most suitable for this kind of project with novice users.

Figure 4. Users collaborating with the Time2sketch software.

CONCLUSION

To conclude, the variability of the VR sketches is the result of three inter-individual factors (visuo-spatial abilities, drawing and VR experience and, spatial inspection) impacting three criteria (volume, proportions, and fidelity). VR experience impacts the proportions, although drawing experience impacts mainly the fidelity. The mental rotation skills impact all the criteria (except for de volume in task 2). Finally, spatial inspection and movements impact the volume and the proportions of complex shapes. The VR sketching software was found to be easy to use even though recent field studies [7] have shown that users are not satisfied with the final productions, which are considered too ambiguous. Nevertheless, this ambiguity can be beneficial for the ideation. Solutions to improve the user experience still need to be found. For this, we suggest that teams with complementary profiles (in terms of visual-spatial ability, drawing and VR experiences) be encouraged to communicate their ideas during the ideation phase.

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