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Immersive 3D sketching tools: implications for visual thinking and communication

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ABSTRACT

Paper-based (PB) sketching involves the challenge of representing three-dimensional (3D) shapes on two-dimensional (2D) surfaces. The recent generation of virtual reality (VR) sketching tools offer a way to overcome this challenge. These immersive 3D sketching environments permit the rapid construction of freehand stroke-based 3D models in 3D space while replicating the immediate experience of PB sketching. To explore the potential advantages of VR sketching in visual thinking and visual communication, we conducted investigations with sixteen architectural students engaged in PB and VR sketching tasks. We observed their visualization behavior during VR sketching and their behavior in transitioning between PB and VR sketching. The participants' experiences of the two media were also recorded in semi-structured interviews and questionnaires. Our observations show that immersive 3D sketching is a unique form of visual representation that facilitates the rapid and flexible creation of large and detailed (but inaccurate) 3D computer models. It is a multimodal medium that supports visual thinking and communication behaviors associated with PB sketching, CAD modeling, physical model-making and gesturing, all within the same space. This unique combination enables users to engage in visual thinking and visual communication activities in ways that cannot presently be achieved with any other single representation technique.

1. Introduction

Many designers across a range of disciplines and industry sectors work on projects that result in three-dimensional (3D) shapes or exist in 3D spaces. Consequently, much of their work involves imagining and representing 3D shapes. To do this, designers use a variety of media to explore, develop and communicate their ideas, including physical gestures, paper-based (PB) sketches, computer-aided design (CAD) models and physical models. Each form of representation has specific attributes that make them better suited to some applications than others. In the early stages of design, many designers adopt PB sketching for being the most accessible, intuitive and immediate means of exploring, developing and communicating their ideas. Paper-based sketching is often performed freehand with a pencil or pen and without the use of other drawing equipment such as straight edges or a compass. Representing a three-dimensional shape on a two-dimensional sheet of paper presents a challenge that is often met by making two different kinds of planar projection:

- Single-view projections that represent the shape from such an angle that it provides information about all three principal dimensions. An isometric sketch is an example of this, where each principal dimension is equally distorted on the page (see Figure 1).
- Multi-view projections that represent the shape from more than one angle so that collectively, the different views provide useful information about all three dimensions. A set

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of principal views in third angle orthographic projection is an example of this (see Figure 1).

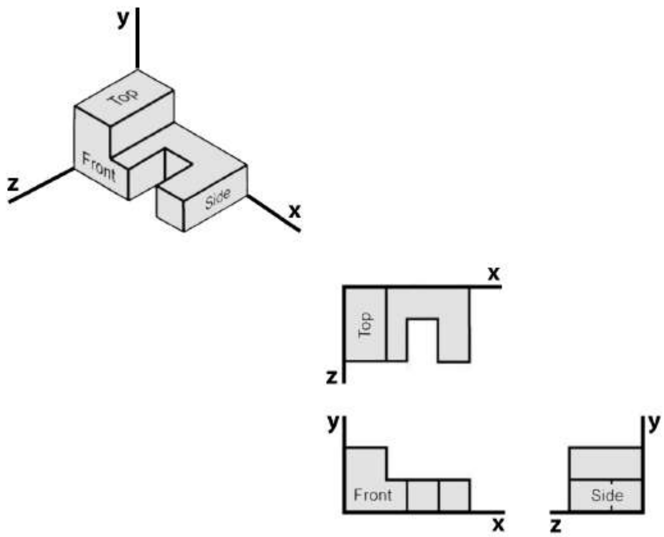

Fig. 1: Three-dimensional object represented in a single view drawing (top left) and multi-view drawing (bottom right).

Planar projections allow three-dimensional shapes to be visualized, recorded and communicated, whether those shapes already exist or are only imagined. However, the process of making projections has some limitations. Projection requires skills that must be learned and practiced to achieve and maintain competence. Some projections can be difficult to read for those who are not familiar with them and intimidating to produce or edit for those who are not experts. Once projections have been produced, viewing the shape from another angle requires a new projection to be made. This either results in the production of numerous projections or in only a limited and inadequate set being used. Especially during early-stage design work, where 3D shapes are being developed and refined, the requirement for projection can act as a barrier to free and flexible visualization.

The challenges associated with representing stroke-based 3D shapes in early-stage design might be addressed by a new generation of immersive 3D sketching tools, which permit users to rapidly make freehand strokes directly in 3D space. These tools offer a different approach to developing 3D CAD models, but the user inputs required to develop these models – and the models that result – have a lot in common with freehand PB sketching. One particular feature of these new tools is that the user wears a head-mounted display (HMD) and waves hand-held controllers around to make strokes, which are then persistently suspended in space (from the perspective of the user, see Figure 2). The user can move around these strokes during the act of sketching and can inspect, add, modify and delete strokes from any angle of view (as well as performing other operations). The user cannot see their physical body or environment but may see an avatar or virtual hand-held controllers in 3D space. HMD can be used with any compatible computer in any room with sufficient space without the need for extra equipment or modification of the room.

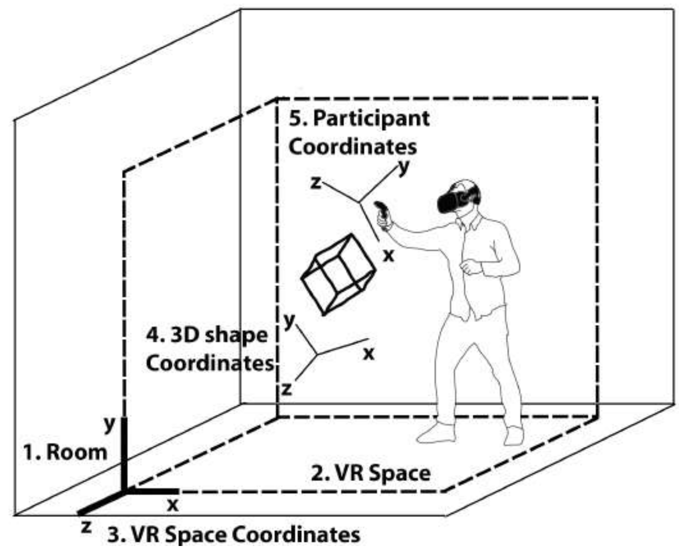

Fig. 2: The relationship between users and 3D shapes when using an HMD system for immersive 3D sketching.

The opportunity to produce freehand sketches directly in 3D space, rather than on a sheet of paper (or other flat surfaces), has profound implications for how users might visualize and communicate 3D shapes and spaces, especially in the early stages of design. To better understand immersive 3D sketching and its implications, we conducted an empirical study to investigate how users work during immersive 3D sketching tasks, focusing on how they represent 3D shapes and spaces in a fully immersive 3D environment. Before reporting on that study, we review the literature related to fully immersive stroke-based 3D sketching, particularly those focusing on the users' impressions and experiences.

2. Literature review

Early studies of immersive 3D sketching were conducted using CAVE (CAVE Audio Visual Experience) and its variant systems. Studies of CAVE sketching have often concluded that stroke-based freehand sketching is an inefficient and imprecise means of representing 3D shapes [1].

For example, a CAVE VR study compared four 3D sketching techniques used for drawing on Air: one-handed drag drawing (drag), two-handed tape drawing (tape), sand and free(hand) to ascertain which was the most accurate and efficient. In the drag technique, a physical stylus is used to control a virtual brush from which strokes are sketched. The stylus and brush are connected via a 'tow rope' such that when the stylus is moved away from the brush, the rope becomes taught and drags the brush in the direction of the stylus. When the stylus is moved towards the brush, the rope becomes slack and the brush is free to move in any direction within the radius of the rope. In the tape technique, both hands are used to sketch strokes. Straight strokes are sketched by holding the non-dominant hand in place while using a stylus to sketch with the dominant hand. The non-dominant hand is moved during sketching To sketch curved or jagged strokes. In the sand technique, a stylus is used freehand with no constraints on its movement except for the haptic feedback from friction and viscosity. The stylus feels as if moving through loose sand. The free(hand) technique involves a stylus with no movement constraints or haptic feedback. The study measured the variance between positional and directional accuracies and the time taken for sketching. The results supported the view that free(hand) 3D sketching had the greatest errors in positional and directional accuracy but also took the least time to perform [2].

Almost a decade later, the same perception persists in HMD sketching studies [3, 4]. There are many CAVE and HMD studies in which researchers and their users expressed frustration and dissatisfaction with stroke-based immersive 3D sketching [3, 1, 5]. Users frequently complained about the difficulties of trying to sketch 3D shapes with accuracy [1, 3]. In many instances, this lack of accuracy was viewed as a negative trait of stroke-based immersive 3D sketching. Many users wanted immersive 3D sketching tools to include stroke snapping, scaling, haptic feedback, visual depth cues, motion parallax and editing tools to circumvent their lack of sensorimotor control [1, 3, 6]. Such findings motivated researchers to conclude that freehand immersive 3D sketching is insufficient, prompting the development of tools with assistive features: that beautify stroke-based freehand sketches to make them look aesthetically pleasing [7]; tools that make the user sketch on virtual planes [3, 7, 8]; tools that create geometries and strokes from hand gestures made by the user [9, 10, 11]; tools that use real-world shapes to guide the placement of sketched strokes [4]. However, immersive 3D sketching tools remain undervalued, misunderstood and unused by many designers who view them as frivolous for serious design tasks [12, 3, 13].

The views of users and researchers regarding the call for assistive features are intriguing, considering that in many of the same studies, the most positive aspects of users' experiences did not involve assistive features. Users perceived an intrinsic value in stroke-based immersive 3D sketching, but did not attribute those perceptions to the use of assistive features. For example, most users preferred immersive 3D sketching over 2D sketching. They saw immersive 3D sketching as the more appropriate medium for creativity [1, 3, 13] and reported that immersive 3D sketching was useful for simplifying spatial perception, supporting cognition and reflection [1, 13, 3]. immersive 3D sketching caused users to rethink their conceptualizations of representing 3D shapes [1, 13] and it altered the way they thought about and performed 2D sketching [1, 13]. Some users, especially those who sketched in 3D before sketching in 2D, reported difficulty with thinking in two dimensions [1, 13]. During immersive 3D sketching, users were observed moving around their sketches to obtain different perspectives; they also sketched most shapes at sizes proportionate to their bodies [1, 13, 14, 3, 15, 16]. Users tried to sit on, look below and walk through their sketched 3D shapes [1, 13, 14].

Solution finding was reported as easier in immersive 3D sketching, as were externalizing, experimenting and communicating ideas [1, 13, 14]. Similarly, users' experiences in VR painting were overwhelmingly positive. VR painting was described as intuitive and exciting. The users reported a sense of comfort and control over paintings. Spatial memory and movement (specifically the ability to walk through paintings and step back to view them as a whole) were reported as being important to the construction of paintings. However, the users reported that immersive 3D sketching was inaccurate [17]. In a recent study of VR painting, users reported that it was useful for communicating 3D conceptual models to clients who may have had difficulty understanding a 2D sketch. Users reported that VR painting was useful for ideation and experimentation of ideas, which felt more concrete in three-dimensions [18]. However, the users were not able to sketch with accuracy and were reluctant to incorporate VR painting into their professional workflows except as a means to explore conceptual forms and ideas [18]. The spatial ability of users was investigated in a recent study of immersive 3D sketching [19]. Users reported that their spatial ability and movement had an effect on the quality of their VR sketches. Users with higher spatial abilities produced more accurate VR sketches than users with lower spatial abilities. However, there were no differences in the quality of users' VR sketches when drawn from a stationary position or while sketching and moving simultaneously in 3D space [19]. The users actively avoided sketching strokes in the participant z-axis. Instead, users chose to move and reorient themselves to sketch in the lateral and diagonal directions from a new position [19].

3. Motivation

Many studies have established that stroke-based freehand immersive 3D sketching is less accurate than PB sketching or immersive 3D sketching with assistive features. However, we argue that such studies have overlooked the potential of immersive 3D sketching as a tool for supporting visual thinking and communication. Other studies of immersive 3D sketching have briefly discussed a few aspects of immersive 3D sketching which relate to visual thinking and communication. Nonetheless, these studies are often general explorations of immersive 3D sketching and discussions regarding visual thinking and communication tend to be incidental. No study specifically investigates the capacity of immersive 3D sketching as a tool for supporting visual thinking and communication. Such a study could be structured around the visual thinking and communication skills commonly used by designers. This would permit a more nuanced understanding of how designers experience stroke-based immersive 3D sketching and the role it might play in design work. The classification of visual thinking skills (see Table 1) represents the types of thinking and acting most common to designers who work with 3D shapes [20]. The purpose of our study is to understand how immersive 3D sketching supports visual thinking and communication. For the sake of clarity of comparison against PB sketching, we will refer to immersive 3D sketching as VR sketching and 3D space as VR space throughout the methodology and the results sections.

Table 1: Classification, definitions and indicators for measuring visual thinking

Visual thinking criteria	Indicators
Visual transformation (mental image manipulation)	Recalling object shapes, relationships, location, object attributes (colour, texture etc).
Visual synthesis	Object/feature recognition; understanding semantic relations; categorization; perceptual speed; image completion.
Visual-spatial reasoning	Affine transformations (rotation, reflection, scaling, etc.,) view transformation; color, texture, attribute transformation; cross-sections; 2D-3D and 3D-2D transformation.
Visual memory	Motion simulation; analogical reasoning; induction; discovering patterns; foldouts; discovering inconsistencies; part removal from assembly; layout/arrangement in constrained space; assembly/disassembly sequence.
Visual comprehension	Generation of new objects; creating images from verbal description; synthesis of 3D object from 2D views; intersections.
Visual expression	Drawing skills; quality of sketching; proportions; clarity of expression; embellishments such as shading.

4. Methodology

4.1. Participants

Sixteen undergraduate architecture students (thirteen women and three men) were recruited for the study. Adverts posted in the Department of Architecture at the University of Cambridge were used for recruitment. Eligibility for the study depended on being in the second or third year of study on the BA Architecture degree, being comfortable in sketching 3D shapes on paper and confident in speaking English fluently. Participants who wore eyeglasses were required to have a good level of unassisted vision or to wear contact lenses for the study. The participants were not asked to present evidence of sketching ability, but admission into the degree programme involves a portfolio assessment. The participants' average age was 20.69 (SD = 0.70) years, with an average of 1.81 years of university education. All the participants described themselves as competent in paper-based (PB) sketching, physical model making and using CAD systems. The participants reported spending an average of 40.31 (SD = 32.42) hours per month PB sketching, 51.94 (SD = 38.58) hours per month making physical models and 84.38 (SD = 36.55) hours per month using CAD tools, primarily AutoCAD (five participants also had experience using Rhinoceros 3D; three used Google Sketchup; one participant used Microstation). None of the participants had any prior experience of sketching in VR. All participants gave informed written consent before starting the study. They were paid £10 for their participation, except for one participant who received an additional [approximately 10 USD] due to technical problems which extended the duration of that session.

4.2. Materials

The study took place in a private room in the Engineering Department of the University of Cambridge. We chose "Gravity Sketch 3D ©" (GSVR) (https://www.gravitysketch.com) for the VR sketching exercises because it allows users to sketch directly into VR space. GSVR provides a wide range of features, including the ability to implement planes and axes of symmetry, create complex surfaces, generate three-dimensional primitives and import CAD geometry. To simplify the interactions, we only provided participants with a single controller, which limited the functionality to freehand line drawing by making individual strokes. Use of a single controller also permitted user variation of stroke thickness and colour (before making the strokes) and permitted delete, undo and copy-paste of strokes (after making the strokes). The ability to select stroke thickness and colour replicated the options available in the paper-based drawing condition (through various implements, ranging from fine pencils to thick ink markers). The ability to undo previous actions, delete strokes, and copy-paste strokes were all features of GSVR that were retained by use of a single controller (actions that were not fully permitted in the paper-based drawing condition). During VR sketching the participants were only able to see the hand-held controller for their sketching hand in VR space. The second hand-held controller for the participants' non-sketching hand was not visible in VR space because it was not used during VR sketching.
The HTC Vive © (https://www.vive.com) was used as the VR system for the study. The participants performed VR sketching in a physical area of 2 by 1.5 meters. To prevent the participants from bumping into the physical walls of the room, a slightly smaller VR space was defined using the HTC Vive. This resulted in a blue grid wall that appeared at the boundaries of the VR space when that boundary was approached (see Figure 3).

Participants were seated at the drawing board during PB sketching, but they stood up for VR sketching. All VR sketches were screen recorded using a VR-capable laptop computer. A wide-angle video camera was used to record the participants' physical actions while VR sketching as they moved around the room. Another video camera was positioned directly above the drawing board to capture the production of the paper sketches. To record the participants' utterances during the study, they wore a lapel microphone connected wirelessly to a radio receiver unit attached to the laptop. To facilitate review and analysis, the video data from the VR sketching sessions was edited

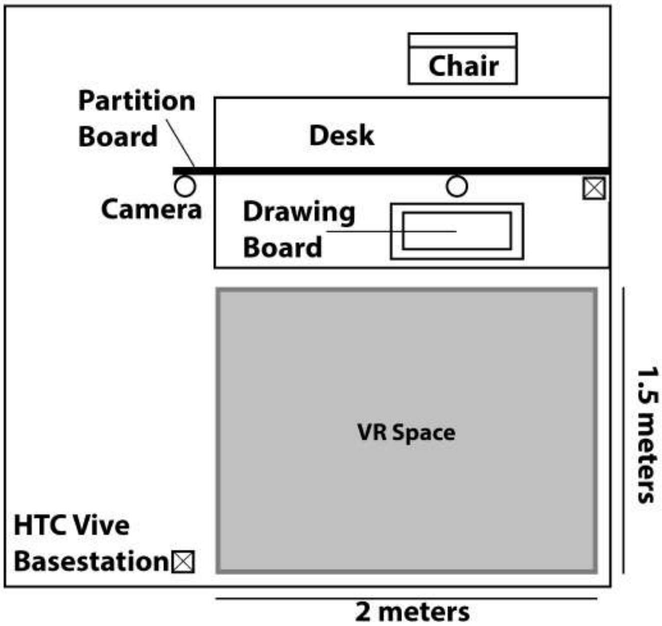

Fig. 3: Diagram of the room used for the VR sketching investigation.

to produce synchronized picture-in-picture videos (see Figure 4) showing the participants' physical actions (e.g. movement in the room) and the images they were producing with those actions (e.g. sketches in VR space).

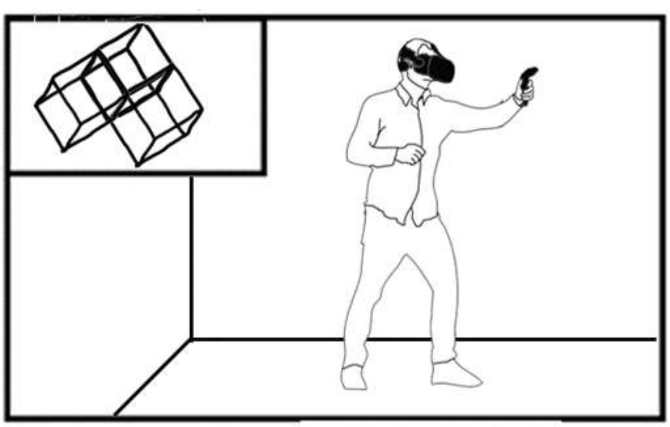

Fig. 4: Picture-in-picture layout. The participant's VR sketch appears overlaid in the small rectangle at the top left of the screen.

4.3. Before sketching

All 16 participants were given scheduled appointments to participate in the study and worked individually during their two-hour sketching session. The participants were divided into four groups: A, B, C and D. Each group had four participants each participant was assigned an alphanumeric identifier: A1, A2, A3, A4, B1, B2, [...], D3, D4. At the start of each session, the researcher gave a brief explanation of the purpose and format of the exercises. The researcher briefly demonstrated the VR sketching tool and participants were given ten minutes to practice VR sketching to their satisfaction. Immediately after the VR sketching practice, the researcher asked all participants for their initial impression of VR sketching. Next, all participants were given an optional five minutes to practice paper-based (PB) sketching on an A3-sized drawing slope while sitting at the desk (all declined due to their experience in PB sketching, see section 3.1) Next; all participants were given a maximum of ten minutes to complete a VR sketching training task in which they were required to sketch 3D shapes according to verbal instructions read by the researcher from a prepared script. All participants were read the same instructions in the same order. They were instructed to think aloud during the training task [21, 22] and had the opportunity to ask the researcher questions about VR sketching.

4.4. During sketching

Each participant completed a total of five VR sketching tasks. Due to safety precautions, none of the participants spent more than 20 minutes continuously wearing the VR Headset (see Table 2). For tasks 1 - 4, each 20-minute VR sketching period was separated by a 10-minute PB sketching period. To eliminate learning effects, in groups A and C, all participants sketched in this order: 10 minutes PB sketching followed by 20 minutes VR sketching. In groups B and D, the sketching order was reversed: 20 minutes VR sketching followed by 10 minutes PB sketching. PB sketching was not included in task five. The participants completed two VR sketching tasks in a single 20-minute period, switching from one task to another without removing the headset (see Table 3). Ten minutes was given to each task because pilot studies showed that the participants' attention began to wane after ten minutes of sketching the same 3D shape.

During the tasks, each participant was shown the 3D shapes as 2D photographs displaying the shape from multiple angles or as CAD models suspended in VR space for that particular task. For example, if participant A1 sketched the 3D shape i on paper for task one, she or he would sketch the 3D shape ii in VR for the same task. In group A, all four participants sketched 3D shape i on paper, then sketched 3D shape ii in VR for each task. In group B, the order was reversed: participants sketched 3D shape ii in VR, then sketched 3D shape i on paper for each task. In group C, 3D shape ii was sketched on paper then 3D shape i sketched in VR. In group D, 3D shape ii was sketched in VR then 3D shape i was sketched on paper.

For tasks 1 – 3, all participants produced one VR sketch and one PB sketch. For task 4, all participants were required to produce only one sketch in PB or VR. The participants were asked to view two 3D shapes, one seen as a series of 2D photographs and the other seen as a 3D model in VR. The participants were asked to commit both shapes to memory and then asked to wait for one minute before sketching the shape that they most remembered as accurately as possible in the medium that the shape was viewed. All participants were given a maximum of 10 minutes. For task 5, all participants produced one VR sketch only (see Table 2). In all tasks, the researcher read instructions aloud to all participants from a prepared script. All participants were instructed to think aloud during VR and PB

Table 2: The tasks of the VR sketching study by visual thinking skills

Task	Visual thinking skill	Number of sketches per task	Time limit (minutes)
1	Visual transformation	1 PB and 1 VR	20
2	Visual synthesis	1 PB and 1 VR	20
3	Visual spatial reasoning	1 PB and 1 VR	20
4	Visual memory and comprehension	1 PB or 1 VR	10
5	Visual expression	1 VR	10

Table 3: Sketching task order by group assignment. Tasks were performed one immediately after the other and the head-mounted display was not removed between consecutive VR tasks.

Group	Task 1	Task 2	Task 3	Task 4
A	PB shape i, VR shape ii	VR shape i, PB shape ii	PB shape i, VR shape ii	PB shape i, VR shape ii
B	VR shape i, PB shape ii	PB shape i, VR shape ii	VR shape i, PB shape ii	PB shape i, VR shape ii
C	PB shape ii, VR shape i	VR shape ii, PB shape i	PB shape ii, VR shape i	PB shape ii, VR shape i,
D	VR shape ii, PB shape i	PB shape ii, VR shape i	VR shape ii, PB shape i	PB shape ii, VR shape i,

sketching [21, 22]. However, the researcher did speak if participants had technical difficulties, such as VR headset malfunctions or to prompt the participants to resume thinking aloud after a prolonged period of silence. During the sketching tasks, the researcher sat out of sight and only emerged to load computer files and to hand paperwork to the participants.

Upon completion of each VR sketch, the researcher handed each participant a second hand-held controller and then instructed each to take a 2D' photograph' of their VR sketch from an angle of their choosing that showed the shape using the camera function within the VR sketching tool. The second hand-held controller was visible to the participants when taking photographs. The participants then saved their VR sketch files.

4.5. After sketching

At the end of the main VR sketching tasks (described below), all participants were interviewed for five minutes regarding their experience of VR sketching during the session. All participants were asked again for their impression of VR sketching to see if there were any changes of opinion and what may have influenced such changes. After the interviews, all participants completed four short surveys, the first being the Sketching questionnaire (created by the researcher) used to measure the effort required for VR sketching and PB sketching. The second was the revised version of the UQO Cyberpsychology lab survey [23] for measuring presence in virtual environments. The questions regarding sound and haptic feedback were not included in the modified VR presence questionnaire. All of these factors necessitated the development of a modified VR sketching presence questionnaire in which certain keywords in the original survey were changed to make the questionnaire directly descriptive of VR sketching. The third questionnaire was the VR Simulator Sickness Questionnaire, used to measure the symptoms associated with the use of a VR headset [24]. The fourth was a questionnaire that collected demographic information and other information about all participants' prior experiences with PB sketching, physical model making and CAD systems. All participants were presented with all four questionnaires in the same order (see supplementary data: 4).

4.6. Sketching tasks

The main part of each session was divided into five VR sketching tasks, which were structured according to Shah, Woodward and Smith's [20] visual thinking skills framework (see Table 1). The visual thinking skills are not mutually exclusive; each task was developed to emphasize one particular design skill even if others were relevant. However, visual memory and visual comprehension were combined in a single task. A total of eight (pre-constructed) 3D shapes were used for tasks 1 – 4, as shown in Table 3. Task 5 did not involve any 3D shapes; therefore, PB sketching was not included.

4.6.1. Task one – visual transformation

This task was designed to explore the participants' experiences of mental image manipulations such as affine transformations (for example, rotation, reflection and scaling). All participants were asked to sketch the 3D version of a 2D bracket and an anvil as accurately as possible. All participants saw two separate third angle orthographic projections of the Bracket and Anvil. The projections displayed the top, front and side view of the shapes, with the top view clearly labeled to avoid ambiguity (see Figure 5).

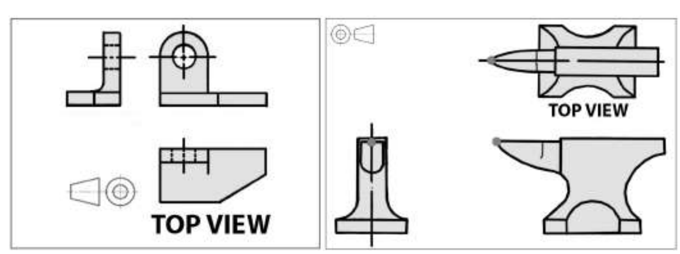

Fig. 5: First angle projection of a bracket (left) third angle projection of an anvil (right)

4.6.2. Task two – visual synthesis

This task was designed to explore the participants' experiences of sketching shapes from verbal descriptions. Sketching, according to verbal instructions, is a common design activity. All participants were asked to sketch additional 3D shapes in sequence as accurately as possible onto two pre-drawn 3D wireframe shapes (see Figure 6). The first pre-drawn shape was a cube with a cylinder on its top face. The participants were instructed as follows:

1. Sketch a second 3D cube sitting on top of the incomplete cylinder.
2. On one face of one of the cubes sketch a triangular-based pyramid.
3. On one face of the triangular-based pyramid sketch a triangular indentation.
4. Change the incomplete cylinder into a complete (hollow) tube.
5. Sketch a torus (3D doughnut) encircling the cylinder.

The second pre-drawn shape was a cube with a square-based pyramid on its top face (see Figure 6). The participants were instructed as follows:

1. On the bottom face of the cube sketch a cylinder extending outwards.
2. Sketch a rectangular indentation on one face of the cube.
3. On the face of the cube opposite the indentation sketch a 3D arrow (make the length of the arrow the same as the length of one edge of the cube).
4. Round off one edge of the cube.
5. Sketch a hemisphere on one of the remaining faces of the cube.

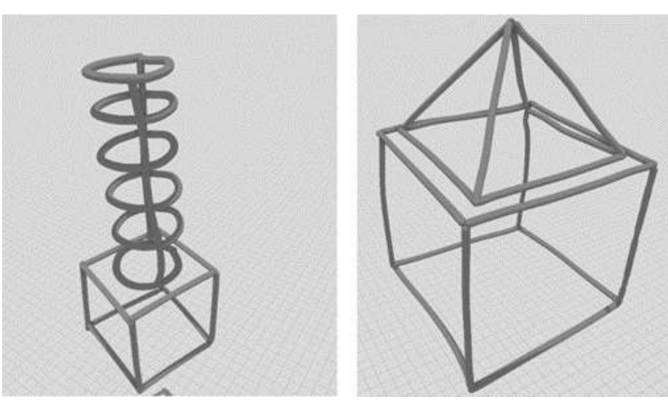

Fig. 6: Pre-drawn 3D wireframe shapes: cube with a cylinder on its top face (left) cube with a square-based pyramid on its top face (right)

4.6.3. Task three – visual spatial reasoning

This task was designed to explore the participants' experiences of sketching multiple interconnecting 3D shapes. All participants were shown an exploded view of a toy train with an assembled view of the same toy train for reference to avoid confusion (see Figure 7). Participants were allowed to view the toy train until satisfied that they understood how the individual parts combined to form the assembled model. The researcher then took the toy train example away and showed participants an exploded view of either a caster wheel or a birdhouse (depending on participant group) to be sketched in assembled view (see Figures 8 and 9).

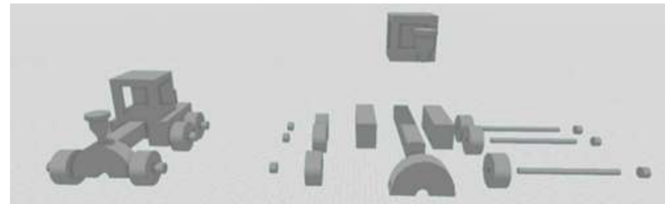

Fig. 7: An example of a toy truck in the assembled view (left) and in the exploded view (right).

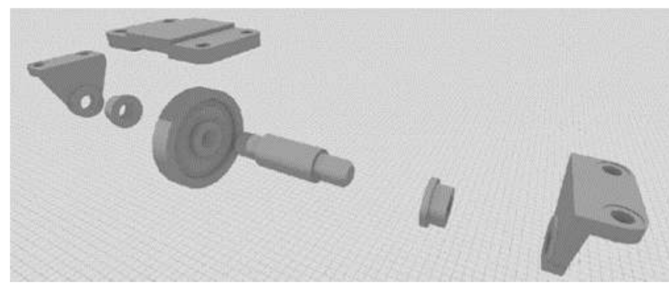

Fig. 8: The exploded view of a caster wheel.

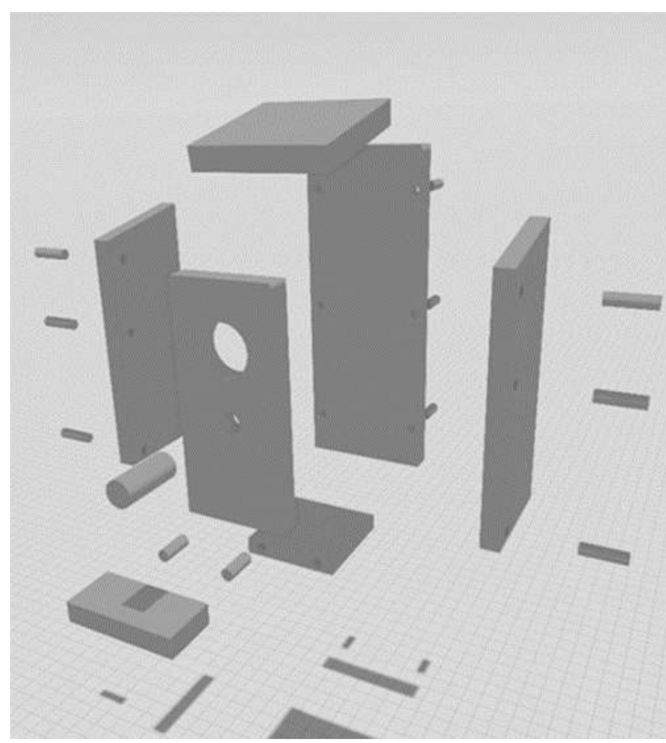

Fig. 9: The exploded view of the birdhouse.

4.6.4. Task four – visual memory and comprehension

This task was designed to explore the participants' experiences of recalling shapes. All participants were shown 2D photographs of a toy car or a toy plane (depending on participant group) taken from several angles. The participants were also shown the same 3D shapes as CAD models in VR space (see Figure 10). All participants were given the following verbal instructions:

1. (To participants in group A). Please look at the 3D shape printed on the photographs and form an accurate image of it in your mind. You may take as long as you need to look at the 3D shape. When you are satisfied with the image of the 3D shape in your mind, I will take it away.
2. When you feel ready, I will show you another 3D shape in the VR sketching space. Please look at the object and feel free to move, rotate and walk around it and form an accurate image of it in your mind.
3. When you feel ready, you may view both 3D shapes again as many times as you need. When you are satisfied with the images of the 3D shapes in your mind, I will take both of them away.
4. Please wait for one minute and then sketch the object that you most remember as accurately as possible in the same medium that you saw it.

Therefore, if the shape was seen as a 2D photograph, then it was sketched by the participant on paper; if seen in VR space, the shape was sketched in VR. The participants in groups A and C viewed the first 3D shape as 2D photographs, before viewing the second 3D shape in VR. The participants in groups B and D viewed the first 3D shape in VR before viewing the second 3D shape as 2D photographs. The 2D photographs were pictures of the 3D shapes (see Figure 10).

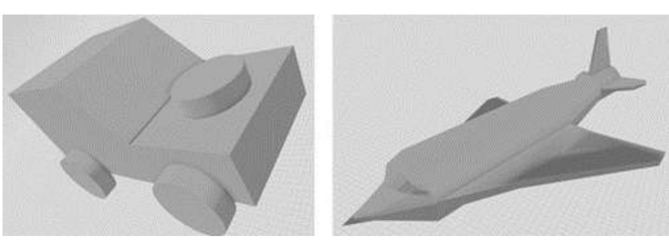

Fig. 10: Toy car (left) and toy plane (right)

4.6.5. Task five – visual expression

This task was designed to explore the participants' experiences of freehand sketching without constraints or instructions. In this task, all participants were asked to sketch in VR space anything of their choosing.

4.7. Data handling and analysis

Concurrent protocol analysis was used to analyze the design behaviors of all participants during VR sketching [25]. Below are the steps used.

1. Conduct and video record the sketching tasks.
2. Edit the video recordings into a single video file for all participants showing their gestures synchronized with the strokes made in the VR sketching space and include their post-sketching interview.
3. Split the edited video recordings into smaller segments (see supplementary data: 5).
4. Encode the segments using a coding scheme (see supplementary data: 5).
5. Analyze and interpret the encoded segments.

Inductive thematic analysis was used to identify common themes in participant interview responses (Braun and Clarke, 2006). Below are the steps used in the analysis.

1. Transcribe the interviews.
2. Read the transcripts and generate appropriate codes (see supplementary data: 5).
3. Collate the codes into categories to enable the identification of the visual thinking and communication skills the participants used during VR and PB sketching.
4. Identify themes that emerge from the codes.
5. Generate questions and topics for future areas of research based on themes.

The 2D 'photographs' taken at the end of each VR sketching task were compared to the participants' PB sketches to view any similarities or differences in the angles and perspectives used to portray the 3D shapes. A visual analog scale was used to measure the continuous data from the VR sketching questionnaire. Due to the small sample size, responses from the VR presence and the simulator sickness questionnaires [24] were tallied.

5. Results

We present the findings of our study as a series of observations derived from the participants' PB and VR sketching sessions, the questionnaires they completed and content analysis of the interviews. Notably, across our different forms of data, the results did not vary with participant grouping, indicating that the order in which they sketched (i.e., PB first or VR first) for each task was not influential.

5.1. Observed behaviour

We observed several behaviors exhibited by the participants during the VR sketching tasks. The majority of participants quickly adapted to immersive 3D sketching without requiring further instruction after the initial training task. The participants quickly understood how to make different types of strokes (changing color, default thickness, and speed-dependent thickness).

In task one (visual transformation), it became apparent that many of the participants struggled to generate accurate curved strokes on paper and in VR space. When working in VR space, many participants preferred to sketch the two planes of the Anvil before sketching curved strokes to connect those two planes. Therefore, the planes acted as guides to help participants position their curved strokes. Only a few participants sketched curved strokes without connecting them to another plane. Nearly all of the participants complained about the difficulty of sketching accurate straight lines and planes with no visual guides, measurement references, or automatic stroke correction. The responses to question 11 represent an almost unanimous perception that achieving accuracy requires much greater effort in immersive 3D sketching (see Figure 12). Similar results were found in previous research[19, 3, 41]

In task two (visual synthesis), the issue of how to sketch curved strokes and surfaces in VR space continued to be apparent. The participants used different stroke thicknesses to convey the solidity of curved surfaces. In VR space and PB sketching, most participants sketched the torus that encircled the cylinder as a wireframe made of rings. Nonetheless, two of the participants used a single, very thick stroke to sketch the torus. The two participants thought that the thickness of the stroke was sufficient to convey the surface's solidity.
In task three (visual-spatial reasoning), the same stroke thickness techniques appeared. Some participants found task three quite challenging. We observed several participants attempting to trace the caster wheel and the birdhouse. Some participants chose to trace strokes directly along the edges of the caster wheel CAD model. Others chose to stand to view the caster wheel in elevation and then sketched strokes according to along the edges of the CAD model but without sketching directly on it. The participants who sketched directly on the edges the CAD model also struggled to sketch the likenesses of the 3D shapes in tasks in tasks one and two.
In task four (visual memory and comprehension), most participants chose to sketch the toy car instead of the toy plane. The two participants that sketched the plane did so in VR space but struggled to accurately represent the plane.

In task five (visual expression), many of the participants took the opportunity to sketch models of buildings for an assignment on the architecture degree course. Some participants stated that VR sketching allowed them to see perspectives which they had either overlooked or did not see in their priorly constructed physical and CAD models. These participants stated that they would modify their physical and CAD models once they return to their degree course. We found that VR sketching did not support the participants' ability to sketch curved strokes accurately in VR space. However, VR sketching did support the ability to make and revise decisions about their sketches, as indicated in questions 2 and 3 of Figure 12.

We did not record any figures regarding the participants use of features such as delete, undo and copy-paste. However, we did observe that all participants made use of the features. We did not observe any variation among the groups. Even the participants who preferred PB sketching made frequent use the features. There was not much variation between the groups regarding VR sketching. Nonetheless, we did observe variations in the preferences of individual participants regarding the effort used for PB and VR sketching.

5.2. Sketching effort

The Sketching Effort questionnaire asked questions about the effort required for twelve aspects of VR and PB sketching (see Table 4). Participants estimated the effort required for each aspect, assigning a score between 0 and 100 percent. From this, we calculated the 'relative PB-VR effort' for sketching for each of the twelve aspects of sketching that participants were asked about (with the effort required for VR sketching subtracted from the effort required for PB sketching). Table 4 shows a count of the number of participants indicating whether more effort was required for VR sketching or PB sketching). This gave a picture of the degree to which each participant found either PB or VR sketching to require more effort (see Figure 11 and Figure 12). For example, participant B3 reported that VR and PB sketching required very little effort, except in four aspects of sketching. In contrast, participant D3 reported that a lot of effort was required for both VR and PB sketching, across multiple aspects.

In general, the participants reported that VR-sketching required more effort in judging the quality of sketches, making modifications, adding embellishments, changing stroke details and conveying the meaning of their sketches to others. Although there was a consensus that VR sketching required more effort than PB sketching, this was not the case concerning decision making (see Figure 12, question 2) and revising decisions (question 3). The participants frequently mentioned that moving around their sketches in VR space improved their decision making and revision of decisions.

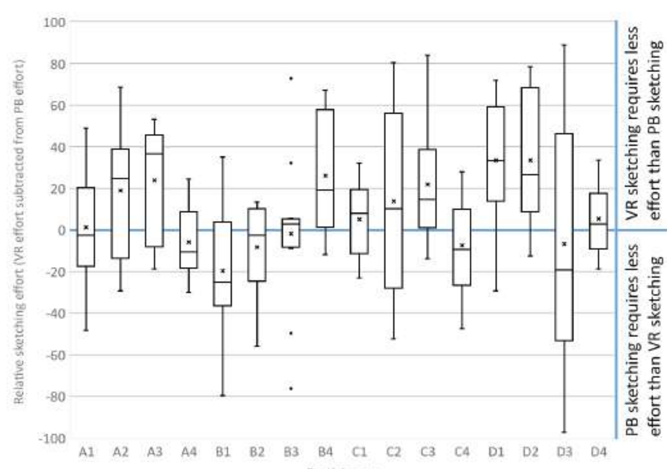

Fig. 11: Self-reported relative PB-VR effort scores for each question *according to the individual responses of each participant*. Positive scores indicate greater VR effort. The boxes display the spread of effort scores between the first and third quartiles. The horizontal line inside the box is the median effort score. The dots are outliers, which are more than two standard deviations away from the mean.

5.3. Impressions of PB and VR sketching

All participants agreed that VR sketching was novel, useful and felt intuitive and natural in comparison to 3D CAD. None saw VR sketching as the digital equivalent of PB sketching. They were of the opinion that PB and VR sketching required different thought processes and reported differences in the ways that they visualized 3D shapes in PB and VR sketching. All

Table 4: Count of participants who indicated that a certain mode of sketching (VR or PB) required less effort. The count of participants who attributed equal effort to each mode are indicated in the 'No difference' column.

#	Question: How much effort was needed to…	VR sketching	PB sketching	No difference
Q1	understand your sketches?	9	7	0
Q2	make decisions about your sketches?	2	13	1
Q3	revise decisions about your sketches?	4	11	1
Q4	generate new ideas for your sketches?	7	9	0
Q5	judge the quality of your sketches?	14	1	1
Q6	modify your sketches?	8	8	0
Q7	embellish (annotations, hatching, arrows, etc.) your sketches?	12	4	0
Q8	structure your sketches?	9	7	0
Q9	view the evolution of your sketches?	11	5	0
Q10	change line details (thicknesses, colours) your sketches?	10	5	1
Q11	sketch with accuracy?	15	1	0
Q12	convey meaning in your sketches?	8	7	1

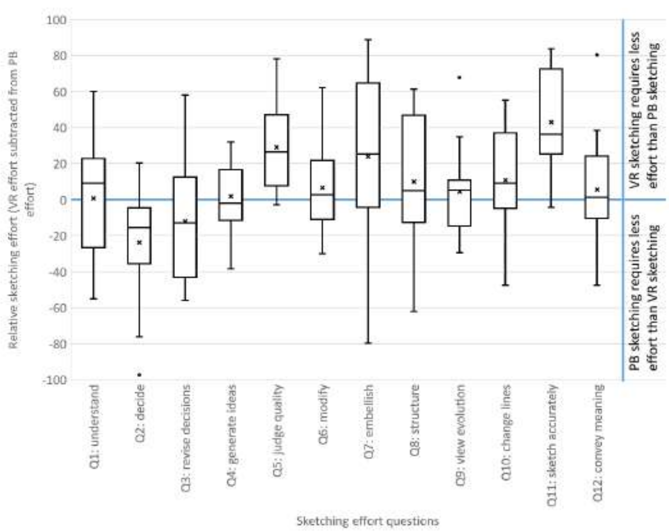

Fig. 12: Self-reported relative PB-VR effort scores for each question *grouped by all responses to that question*. Positive scores indicate greater VR effort. The boxes display the spread of effort scores between the first and third quartiles. The horizontal line inside the box is the median effort score. The dots are outliers, which are more than two standard deviations away from the mean.

thought that VR sketching required more effort in judging the quality of sketches, making modifications, adding embellishments, changing stroke details and conveying the meaning of their sketches to others and sketching with accuracy (see supplementary data: 1).

> *I think VR gives you more perspective. So, where we can look at it from all different angles, therefore, we were able to have a better understanding of the options, as you've been given falsehoods [on paper] of the same thing. Like one picture taken from a different angle, it takes one more step to get your brain to kind of assemble the pictures together. You think about where the pictures been taken from, which angle, how that picture is connected with that one, but with VR, you are just turning around things. - Participant C3*

The participants could be divided according to whether they preferred VR sketching over PB sketching or preferred PB sketching over VR sketching. Those favorable to VR sketching felt that it was easier to sketch and immediately comprehend 3D shapes in VR space than it was to draw the same shapes on paper or construct them using a CAD tool. They reported that body movement enabled better comprehension of 3D shapes, an improved ability to visualize 3D shapes and an increased sense of creativity. Moving around their VR sketches enabled them to consolidate or evoke mental imagery in a way that is not possible with PB sketching. They also valued the ability to sketch at large scales and the ability to rapidly construct sketches without using real materials. Some participants entered and inhabited their sketches, which contributed to a sense of creative freedom reported by the majority of participants.

Those preferring VR exhibited a much more negative attitude towards PB sketching. Those who preferred VR became very aware of the limitations of PB sketching in comparison to VR sketching. They felt very constrained when sketching on paper due to its limited size and struggled to sketch single-view projections of 3D shapes. They felt that in PB sketching, they could no longer use the affordances they had relied on in VR space. They mentioned feeling a loss of movement, a loss of sketching at life scale, loss of multiple viewing angles and a loss of interaction with their sketches. These participants also observed that in PB sketching more time was spent thinking how to plan and visualize the representation of 3D shapes as opposed to VR sketching where less thinking was involved.

In contrast, participants who favored PB sketching expressed opposite views. These participants were glad to sketch on paper after sketching in VR space. They felt that PB sketching was more natural than VR sketching and found it quite difficult to sketch in VR space. These participants also actively walked around their VR sketches but appeared to dislike the affordances of VR sketching. They did not appreciate the freedom of VR sketching because they had to extra make decisions about their sketches in comparison to PB sketching. They reported that VR sketching required more effort in judging the quality of sketches, making modifications, adding embellishments, changing stroke details and conveying the meaning of their sketches to others. One participant claimed that PB sketching enabled her to comfortably sketch as she pleased, the implication being that VR sketching changed her sketching style in a manner that she disliked. Another participant claimed that PB sketching was more soothing in comparison to the 'always there' intensity of VR sketching. In task 5, one participant even chose to sketch in single view projection despite being in VR space (i.e., by drawing on an imaginary planar surface).

5.4. Representation of 3D shapes in VR sketching

In VR sketching, many participants sketched 3D shapes with fewer supportive and reasoning sketching behaviors such as construction lines, centerlines, practice sketches and under sketches in comparison to other participants who sketched the same 3D shapes on paper. Overall, the participants spent more time in VR sketching in comparison to PB sketching. Many were told to stop sketching, having used the maximum time available (ten minutes). The majority of participants were hesitant during VR sketching and spent much of their time walking in circles, stepping backward and forwards, leaning from side to side, crouching, bending, looking upward, standing on their toes, jumping and even sitting and kneeling on the floor while inspecting their sketches. Some participants also used the floor as a flat surface for sketching. Many participants were also using gestures to work out their 3D sketches. Throughout VR sketching, all participants performed sense-making gestures whenever they were unclear about the construction or arrangement of the sketches. The participants would often point at their VR sketches in mid-air without actually disturbing them in VR space. Similarly, the participants also performed planning gestures using their hands to mark the placement of strokes in mid-air without making strokes in the VR sketching space. These gestures were often accompanied by utterances in which the participants were questioning and clarifying their understanding of their sketched 3D shapes.

At other times the participants were attempting to use gestures to communicate with the researcher. Quite often, the participants were seeking clarification or help regarding the parameters of the task. However, some participants wanted the researcher to provide feedback and assist with decision making; this was indicated by pointing gestures. Some participants even turned their heads in the direction of the researcher while pointing (the researcher did not respond).

In the VR sketching tasks, many participants struggled to sketch 3D shapes with complex curves. In task 1, the participants struggled to sketch the anvil accurately on paper. Many anvils appeared to be twisted, or in the wrong proportion or distorted in their appearance (see Figure 13). In task 2, there was no consensus regarding how to represent the large wireframe cylinder as a solid shape on paper. Some participants sketched long straight vertical strokes; others sketched a smaller wireframe cylinder in the middle of the large cylinder. Another participant simply shaded part of the large wireframe cylinder to indicate the casting of a shadow. In PB sketching, we observed that the majority of participants sketched the torus as a solid shape in single view projection while sketching the top cube in wireframe. However, in VR sketching, the majority sketched the torus as a wireframe because it was easier to copy and paste a circle repeatedly to form the required shapes. Only two participants sketched the torus as a solid shape, but both used thick strokes to indicate the volume of the torus. Also, in task 2, when asked to represent the cylinder as a solid shape, the majority used the same methods as in PB sketching. However, two participants removed the vertical strokes, leaving a series of floating circles to depict the solidity of the cylinder. In task 3, several participants struggled to sketch the caster wheel accurately on paper and especially in VR space where there were more degrees of freedom. In task 4, none of the participants attempted to sketch the cylindrical toy plane on paper. Only two participants sketched the plane in VR space. Both participants used different techniques to represent the plane. One copied and pasted a series of rings to represent the body of the plane; the other used long thick strokes to form a cylinder. Many participants mentioned that it was difficult to visualize how the curves fitted together and that is was difficult to sketch a surface using strokes only.

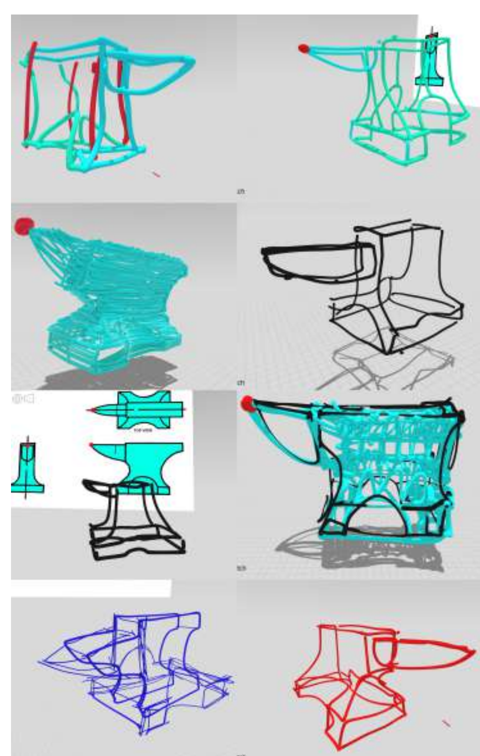

Fig. 13: VR sketches of anvils.

6. Discussion

We found that our participants, in general, struggled to represent curves and curved surfaces on paper and in 3D space. A similar result was found in a previous HMD study of freehand immersive 3D sketching [3]. Our participants struggled to visualize how non-planar curves and surfaces fitted together in PB and immersive 3D sketching. Our participants called for assistive features to make the representation of non-planar curves and surfaces easier in immersive 3D sketching. They were also undecided as to the most efficient means of representing non-planar curves and surfaces. We observed that assistive features and geometries might help some participants to represent complicated 3D shapes with multiple non-planar curves and surfaces. Regarding the visual thinking and communication skills, the participants had difficulties with visual transformation, visual-spatial reasoning and visual memory and comprehension.

Our findings suggest that immersive 3D sketching reduced the need to retain the single view projection of 3D shapes in their minds prior to sketching. The participants moved, sketched and performed mental image manipulations simultaneously. They cited easier mental image manipulation as one of the favorable aspects of immersive 3D sketching. However, many of the participants still struggled to represent non-planar curves and surfaces despite seeing their sketches suspended in 3D space. The participants still had difficulties in representing non-planar curves and surfaces. In task 1, many of the VR sketched anvils did not share many resemblances to their associated 2D multi-view images. Likewise, some of the caster wheel assembly sketches. Some participants were unable to connect the individual parts together. Only two participants attempted to sketch the 3D toy plane and neither sketch bore much resemblance to the plane. These observations may imply that immersive 3D sketching had little impact on the participants' visual transformation, visual-spatial reasoning and visual memory and comprehension, but this is not the case. The same issues with non-planar curves and surfaces were observed in the participants' PB sketches. The participants did not struggle as much to represent 3D shapes with straight edges and flat surfaces. Furthermore, the participants had even less difficulty with visual synthesis and visual expression. The majority of participants preferred stroke-based immersive 3D sketching despite experiencing difficulties with some types of visual thinking and communication. The same participants were also dissatisfied with PB sketching. Their main complaints concerned the visualization of the single-view projection of 3D shapes before and during the immersive 3D sketching tasks.

Our findings suggest that part of the value of stroke-based immersive 3D sketching is in its capacity to challenge participants to think more carefully about the representation and visual communication of 3D shapes. Many participants in our study described the differences in how they visualized 3D shapes during immersive 3D sketching as compared to PB sketching. They stated that immersive 3D sketching affected how they understood 3D shapes and their approaches towards PB sketching. In PB sketching, our participants stated that they gave a lot of attention to planning how to sketch single view projections before making strokes on paper. However, during immersive 3D sketching our participants were able to plan and sketch 3D shapes simultaneously, which meant that they focused more on understanding how to represent 3D shapes [3].

Our participants frequently mentioned the importance of moving around and interacting with VR sketches with regard to their comprehension. Similar findings were reported in previous CAVE and HMD stroke-based immersive 3D sketching studies [26, 1, 13, 3]. We observed that immersive 3D sketching has multimodality that is not present in other forms of CAD tools or in PB sketching.

In social semiotics, multimodality denotes that there are multiple ways of understanding, interpreting and making meaning [27]. Multimodality, when applied to immersive 3D sketching, describes a tool that enables designers to simultaneously sketch and model 3D shapes and seamlessly interpret those shapes as a sketch or as a model with ease. For example, the association between movement and perception of 3D spatial dimensions and relationships has been widely documented as one of the advantages of working with physical models [28, 29, 30]. The multimodality of immersive 3D sketching aided the participants with the translation of mental imagery from the mind to 3D space. The majority of participants felt that it was easier to sketch 3D shapes directly into 3D space than using other approaches such as PB sketching. The participants defined mental imagery as the 3D shapes seen within their minds.

Even when presented with 2D multi-view images, the participants described them as 3D shapes. The majority of our participants saw immersive 3D sketching as a new way of modeling, not a new type of sketching. Our participants frequently made statements such as "I was modeling a sketch" or "I was sketching a model." The participants perceived their immersive 3D sketches to contain attributes common to PB sketching, such as disposability, speed, minimal detail [31]. However, they also perceived their Immersive 3D sketches to contain attributes common to physical 3D modeling. For example, during immersive 3D sketching, many participants became thoroughly engrossed and indicated an aversion to colliding with their Immersive 3D sketches even though the sketching area was clear and the participants were able to move freely. When producing new strokes or copying existing strokes, the participants often contorted their arms and bodies to avoid contact with their immersive 3D sketches; this was the case even when it would have been much more convenient to move into or through existing strokes which were, of course, virtual and could not be disturbed by the participants 'colliding' with them. A similar finding was previously reported in which participants contorted their bodies as they moved around 3D shapes [16]. Nonetheless, our observations of participants contorting their bodies to sketch from awkward positions have not been previously reported. We argue that stroke-based immersive 3D sketching does support visual thinking and communication. Our participants spent more time focused on the forms of 3D shapes rather than the projection of those shapes. However, they still struggled to sketch non-planar curves and surfaces.

6.1. Limitations

There were some limitations in our study. The first being our small sample of 16 participants, which limits our statistical analysis of the data. However, it does permit an in-depth study of each participant's behavior and utterances. The participants were all first-time users of immersive 3D sketching and part of their judgment may have been affected by the novelty of the experience. Many participants used a maximum of 10 minutes for each immersive 3D sketching task, which implies that a longer time limit may have been necessary. Nonetheless, there is no consensus regarding time limits in VR or PB sketching studies. In preparation for the study, the researcher conducted several pilots and found that our participants became agitated beyond two hours. Our study was 2 hours long from start to finish including the pre- and post-visualization tasks, another sketching study was 90-120 minutes in duration [4].

In other studies, users only needed 10 minutes to produce sketches using 3D sketching tools [32, 9, 14, 9, 33, 34]. Our pilot studies showed that participants' attention started to wane after 10 minutes. None of the participants required the 5 minutes of PB training offered in the pre-visualization tasks of the study.

We did not recruit participants with equal levels of expertise in PB and immersive 3D sketching. Nor did we account for the spatial perception abilities of the participants in our sampling. Although our participants all sketched on paper often, none had previously used any form of immersive 3D sketching tool. As such, our participants can be considered experts in PB sketching but novices in immersive 3D sketching.

During immersive 3D sketching, our participants' spatial perceptions may have been compromised by their physical bodies and the surrounding environment being invisible to them. In augmented reality (AR), people can typically see their own physical bodies and environments, which can strengthen the influence of vision on multisensory interactions [35, 36]. However, people can also quickly adapt their own visual, vestibular, and proprioceptive systems in virtual environments. Many of our participants did not express any form of annoyance at not being able to see their non-sketching hand while making strokes and measuring distances. Instead, such participants were seemingly comfortable relying on proprioception, even if they did express frustration with not being able to use both hands for editing their sketches. Some participants evidently wanted to use both hands for scaling and beautifying existing stokes. Participants who are experienced or expert in immersive 3D sketching may have offered more nuanced insights into how immersive 3D sketching supports visual thinking and communication.

The sketching area was the minimum size available and may have constrained some of the participants' design behaviors for fear of walking into a wall. Our study could have done more to understand the nuances of participants' movements during immersive 3D sketching. We understood why the participants moved, but we could have explored how movement varies between participants. Were there patterns present in the movements? If so, what do the patterns indicate? Is the amount of movement exhibited by participants correlated with their level of comprehension of the 3D shapes? If so, what causal mechanisms are at play and what other factors are involved?

6.2. Future work

In addition to addressing the limitations and questions discussed above, future immersive 3D sketching studies should investigate participants preferences regrading PB or VR sketching in granular detail. Further methods such as a follow-up survey may reveal even more granular information that may offer a more nuanced understanding of why some participants preferred VR sketching over PB sketching and vice versa. The relationship between spatial perception movement and comprehension of 3D shapes in greater depth. There are several methodologies that could be used such as naturalistic observation, ethnography and motion tracking. There is a strong need for immersive 3D sketching studies that make observations over a prolonged period, as much of what is known about immersive 3D sketching is derived from short-term studies. The participants in such a study could be design experts well experienced in immersive 3D sketching to negate the novelty factor and induce a more objective or dispassionate perspective on the technology and its uses. Such work could also focus on design behaviors applied to real-world projects to ascertain when and how immersive 3D sketching fits into design processes. Other possible studies include the observation of group immersive 3D sketching sessions to view similarities and differences between individual immersive 3D sketching and group sketching.

During the immersive 3D sketching tasks, the non-sketching controller was withheld from the participants and thus not visible to them virtually. Also, because it was a VR (rather than AR) implementation of immersive 3D sketching, participants were unable to see their bodies while they undertook the tasks. Questions remain about whether the visibility of a second virtual controller or the participants' bodies would have changed their behavior. Being able to see a second controller or both arms would mean that participants' estimations of position, scale and movement would not depend entirely on proprioception but could also exploit additional visual cues. However, when handed the second controller to take a picture of their immersive 3D sketches, many participants continued to display an aversion to collisions and also continued to position and contort their bodies to find an aesthetically pleasing angle to capture their sketches.

In the supplementary data that accompanies this paper we made a series of observations regarding the participants uses and preferences for VR and PB sketching in observation 7 wrote that the researchers observed that participants' preferences for VR or PB sketching were influenced by some characteristics of the participants, which may also account for their feelings of frustration. There were two groups of preferences among the participants regarding VR and PB sketching. The first group of preferences were expressed by participants that were favorable towards VR-sketching. These participants were surprised by a sense of naturalness which came from sketching lines directly into VR space.The second group of preferences were favorable of PB sketching these participants were glad to sketch on paper after sketching in VR space. These participants felt that PB sketching was more natural than VR-sketching; they found it difficult to sketch in VR space. Further reasons are given in the supplementary data. However, we welcome future studies that will explore our participants preferences in greater depth. Our observations were based on the responses, utterances and behavior of our participants. Future studies with much larger samples may corroborate our findings and discover new phenomena not mentioned in this paper.

7. Conclusion

Immersive 3D sketching is a unique form of visual representation that facilitates the rapid and flexible creation of large and detailed (but inaccurate) 3D computer models. Immersive 3D sketches are built intuitively by the designers as they move about their work. Immersive 3D sketching is a multimodal tool that supports design behaviors associated with PB sketching, CAD modeling and physical model making within the same space. This enables participants to make decisions (communications, analyses, evaluations, revisions) that cannot be made as conveniently in any of the individual modes alone. It is the ability to switch decision making seamlessly through these modes that make immersive 3D sketching useful to the designer. However, immersive 3D sketching does have limitations because although it resembles PB sketching, CAD modeling, and physical model making, it is not quite any of these things. It is possible to make better decisions in each of the individual modes because each mode has information that cannot be easily represented or replicated in immersive 3D sketching. For example, the rich tactility of physical model making is lost in exchange for the rapidity of sketching a 3D model in 3D space, although some forms of haptic feedback can be re-introduced [37] [38]. Proprioceptive and tactile feedback can be useful for confirmation of user input, gestural interactions, and even increasing the participants' sense of immersion in VR [39]. However, adding physically realistic haptic feedback to immersive 3D sketching may also increase complexity, as the tool must be capable of supporting tactility [40]. Some designers, who are very used to making decisions in any of the individual modes (PB sketching, CAD modeling and physical model making), may not see the value of immersive 3D sketching, especially when the precise representation of 3D shapes is needed. Nonetheless, the benefits of immersive 3D sketching outweigh its drawbacks because of its multimodality, which effectively makes immersive 3D sketching a tool that simultaneously supports behaviors that are commonly only found in PB sketching, CAD modeling and physical model making. At present, no other tool provides the designer with this uniquely useful combination.

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References

[1] Israel, J, Wiese, E, Mateescu, M, Zöllner, C, Stark, R. Investigating three-dimensional sketching for early conceptual design—results from expert discussions and user studies. Computers & Graphics 2009;33(4):462–473. URL: http://www.sciencedirect.com/science/article/pii/S0097849309000855. doi:https://doi.org/10.1016/j.cag.2009.05.005.

[2] Keefe, D, Zeleznik, R, Laidlaw, D. Drawing on air: input techniques for controlled 3d line illustration. IEEE Transactions on Visualization and Computer Graphics 2007;13(5):1067–1081. doi:10.1109/TVCG.2007.1060.

[3] Arora, R, Kazi, RH, Anderson, F, Grossman, T, Singh, K, Fitzmaurice, G. Experimental evaluation of sketching on surfaces in VR. In: Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems. CHI '17; 2017, p. 5643–5654. URL: http://doi.acm.org/10.1145/3025453.3025474. doi:10.1145/3025453.3025474.

[4] Arora, R, Habib Kazi, R, Grossman, T, Fitzmaurice, G, Singh, K. Symbiosissketch: combining 2D and 3D sketching for designing detailed 3d objects in situ. In: Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems. ACM. ISBN 0-89791-657-3; 2018, p. 213–222. URL: https://doi.org/10.1145/3173574.3173759.

[5] Wiese, E, Israel, JH, Meyer, A, Bongartz, S. Investigating the learnability of immersive free-hand sketching. In: Proceedings of the Seventh Sketch-Based Interfaces and Modeling Symposium. SBIM '10; 2010, p. 135–142. URL: http://dl.acm.org/citation.cfm?id=1923363.1923387.

[6] Novotny, J, Tveite, J, Turner, ML, Gatesy, S, Drury, F, Falkingham, P, et al. Developing virtual reality visualizations for unsteady flow analysis of dinosaur track formation using scientific sketching. IEEE Transactions on Visualization and Computer Graphics 2019;25(5):2145–2154. doi:10.1109/TVCG.2019.2898796.

[7] Barrera Machuca, MD, Asente, P, Lu, J, Kim, B, Stuerzlinger, W. Multiplanes: assisted freehand VR drawing. In: Adjunct Publication of the 30th Annual ACM Symposium on User Interface Software and Technology. UIST '17; ACM; 2017, p. 1–3. URL: http://doi.acm.org/10.1145/3131785.3131794. doi:10.1145/3131785.3131794.

[8] Mohanty, RR, Bohari, UH, Vinayak, , Ragan, E. Investigating force-feedback in mid-air sketching of multi-planar three-dimensional curve-soups. In: 38th Computers and Information in Engineering Conference. IDETC-CIE '18; 2018,URL: https://doi.org/10.1115/DETC2018-86141. doi:10.1115/DETC2018-86141.

[9] Kim, Y, An, SG, Lee, JH, Bae, SH. Agile 3D sketching with air scaffolding. In: Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems. CHI '18; ACM; 2018, p. 238:1–238:12. URL: http://doi.acm.org/10.1145/3173574.3173812. doi:10.1145/3173574.3173812.

[10] Huang, J, Rai, R. Conceptual three-dimensional modeling using intuitive gesture-based midair three-dimensional sketching technique. Journal of Computing and Information Science in Engineering 2018;18(4). URL: https://doi.org/10.1115/1.4040982. doi:10.1115/1.4040982; 041014.

[11] Alkemade, R, Verbeek, FJ, Lukosch, SG. On the efficiency of a VR hand gesture-based interface for 3D object manipulations in conceptual design. International Journal of Human–Computer Interaction 2017;33(11):882–901. URL: https://doi.org/10.1080/10447318.2017.1296074. doi:10.1080/10447318.2017.1296074. arXiv:https://doi.org/10.1080/10447318.2017.1296074.

[12] Tano, S, Yamamoto, S, Dzulkhiflee, M, Ichino, J, Hashiyama, T, Iwata, M. Three design principles learned through developing a series of 3D sketch systems: "memory capacity", "cognitive mode", and "life-size and operability". In: 2012 IEEE International Conference on Systems, Man, and Cybernetics (SMC). 2012, p. 880–887. doi:10.1109/ICSMC.2012.6377839.

[13] Israel, JH, Mauderli, L, Greslin, L. Mastering digital materiality in immersive modelling. In: Proceedings of the International Symposium on Sketch-Based Interfaces and Modeling. SBIM '13; ACM; 2013, p. 15–22. URL: http://doi.acm.org/10.1145/2487381.2487388. doi:10.1145/2487381.2487388.

[14] An, SG, Kim, Y, Lee, JH, Bae, SH. Collaborative experience prototyping of automotive interior in VR with 3D sketching and haptic helpers. In: Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications. Automotive UI '17; ACM; 2017, p. 183–192. URL: http://doi.acm.org/10.1145/3122986.3123002. doi:10.1145/3122986.3123002.

[15] Hinckley, K, Pausch, R, Goble, JC, Kassell, NF. A survey of design issues in spatial input. In: UIST '94 Proceedings of the 7th annual ACM symposium on User interface software and technology. ACM. ISBN 0-89791-657-3; 1994, p. 213–222. URL: https://www.microsoft.com/en-us/research/publication/a-survey-of-design-issues-in-spatial-input/.

[16] Arnowitz, EM, C. Greenberg, DP. Vspline physical design and the perception of scale in virtual reality. In: ACADIA 2017: DISCIPLINES Disciplines & Disruption Proceedings of the 37th Annual Conference of the Association for Computer Aided Design in Architecture. ACADIA '17; 2017, p. 110–117. URL: http://papers.cumincad.org/data/works/att/acadia17_110.pdf.

[17] Keefe, DF, Feliz, DA, Moscovich, T, Laidlaw, DH, LaViola, JJ. Cavepainting: a fully immersive 3d artistic medium and interactive experience. In: Proceedings of the 2001 Symposium on Interactive 3D Graphics. I3D '01; New York, NY, USA: Association for Computing Machinery. ISBN 1581132921; 2001, p. 85–93. URL: https://doi.org/10.1145/364338.364370. doi:10.1145/364338.364370.

[18] Herman, LM, Hutka, S. Virtual artistry: virtual reality translations of two-dimensional creativity. In: Proceedings of the 2019 on Creativity and Cognition. C;C '19; New York, NY, USA: Association for Computing Machinery. ISBN 9781450359177; 2019, p. 612–618. URL: https://doi.org/10.1145/3325480.3326579. doi:10.1145/3325480.3326579.

[19] Barrera Machuca, MD, Stuerzlinger, W, Asente, P. The effect of spatial ability on immersive 3D drawing. In: Proceedings of the 2019 on Creativity and Cognition. C '19; New York, NY, USA: Association for Computing Machinery. ISBN 9781450359177; 2019, p. 173–186. URL: https://doi.org/10.1145/3325480.3325489. doi:10.1145/3325480.3325489.

[20] Shah, JJ, Woodward, J, Smith, SM. Applied tests of design skills—part II: visual thinking. Journal of Mechanical Design 2013;135(7). URL: https://doi.org/10.1115/1.4024228. doi:10.1115/1.4024228; 071004.

[21] Chrysikou, EG, Weisberg, RW. Following the wrong footsteps: fixation effects of pictorial examples in a design problem-solving task. Journal of Experimental Psychology: Learning, Memory, and Cognition 2005;31(5):1134–1148. URL: https://doi.org/10.1037/0278-7393.31.5.1134. doi:10.1037/0278-7393.31.5.1134.

[22] Someren, M, Barnard, Y, Sandberg, J. The think aloud method - a practical guide to modelling cognitive processes. Academic Press London; 1994,URL: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.98.7738&rep=rep1&type=pdf.

[23] Lab, UC. Presence questionnaire (revised by the uqo cyberpsychology lab). 2004. URL: http://w3.uqo.ca/cyberpsy/docs/qaires/pres/PQ_va.pdf.

[24] Kennedy, RS, Lane, NE, Berbaum, KS, Lilienthal, MG. Simulator sickness questionnaire: an enhanced method for quantifying simulator sickness. The International Journal of Aviation Psychology 1993;3(3):203–220. URL: https://doi.org/10.1207/s15327108ijap0303_3. doi:10.1207/s15327108ijap0303_3.

[25] Tang, H, Lee, Y, Gero, J. Comparing collaborative colocated and distributed design processes in digital and traditional sketching environments: a protocol study using the function–behaviour–structure coding scheme. Design Studies 2011;32(1):1–29. URL: http://www.sciencedirect.com/science/article/pii/S0142694X10000475. doi:https://doi.org/10.1016/j.destud.2010.06.004.

[26] Jang, SA, Wakefield, G, Lee, SH. Incorporating kinesthetic creativity and gestural play into immersive modeling. In: Proceedings of the 4th International Conference on Movement Computing. MOCO '17; ACM; 2017, p. 17:1–17:8. URL: http://doi.acm.org/10.1145/3077981.3078045. doi:10.1145/3077981.3078045.

[27] Forceville, CJ. Multimodality: a social semiotic approach to contemporary communication: Gunther Kress, Routledge, London, 2010. Journal of Pragmatics 2011;43(14):3624–3626. URL: http://www.sciencedirect.com/science/article/pii/S0378216611001871. doi:https://doi.org/10.1016/j.pragma.2011.06.013.

[28] Duzenli, T, Yılmaz, S, Alpak, EM. The effects of model making on design and learning in landscape architecture education. Eurasian Journal of Educational Research 2017;17:121–134. doi:10.14689/ejer.2017.70.7.

[29] Dunn, N. The Ecology of the Architectural Model. Bern, Switzerland. Peter Lang UK. 2008. URL: https://www.peterlang.com/view/title/10092.

[30] Hornecker, E. Sketches, drawings, diagrams, physical models, prototypes, and gesture as representational forms. 2007. URL: https://pdfs.semanticscholar.org/af91/cde649e9f0bc53024df1f374ecb2dfcad4e5.pdf.

[31] Buxton, B. - the anatomy of sketching. In: Buxton, B, editor. Sketching User Experiences. Interactive Technologies; Burlington: Morgan Kaufmann; 2007, p. 105 – 114. URL: http://www.sciencedirect.com/science/article/pii/B9780123740373500547. doi:https://doi.org/10.1016/B978-012374037-3/50054-7.

[32] Xu, P, Fu, H, Zheng, Y, Singh, K, Huang, H, Tai, C. Model-guided 3D sketching. IEEE Transactions on Visualization and Computer Graphics 2019;25(10):2927–2939. doi:10.1109/TVCG.2018.2860016.

[33] Morrison, C, Blackwell, AF. BodyPaint: a physical interface. In: Proceedings of the Second International Workshop on Physicality,; vol. 135. 2007, p. 33–35. URL: http://www.physicality.org/physicality2007/.

[34] Igarashi, T, Matsuoka, S, Tanaka, H. Teddy: a sketching interface for 3D freeform design. In: Proceedings of the 26th Annual Conference on Computer Graphics and Interactive Techniques. SIGGRAPH '99; ACM; 1999, p. 409–416. URL: http://dx.doi.org/10.1145/311535.311602. doi:10.1145/311535.311602.

[35] Pusch, A. Visuo-proprioceptive conflicts of the hand for 3D user interaction in Augmented Reality. Human-Computer Interaction. INPG; 2008. URL: https://pdfs.semanticscholar.org/2bc9/fd864825686743de36a04a7cc9654c2848bc.pdf.

[36] Snijders, HJ, Holmes, NP, Spence, C. Direction-dependent integration of vision and proprioception in reaching under the influence of the mirror illusion. Neuropsychologia 2007;45(3):496 – 505. doi:https://doi.org/10.1016/j.neuropsychologia.2006.01.003.

[37] Snibbe, S, Anderson, S, Verplank, B. Springs and constraints for 3D drawing. The Third PHANToM User's Group Workshop; 1998, p. 59–62. URL: https://www.academia.edu/31418701/Springs_and_constraints_for_3d_drawing.

[38] Keefe, D, Zeleznik, R, Laidlaw, D. Tech-note: Dynamic dragging for input of 3D trajectories. ISBN 978-1-4244-2047-6; 2008, p. 51–54. doi:10.1109/3DUI.2008.4476591.

[39] Bakker, T, Verlinden, J, Abbink, D, van Deventer, R. Development of a haptic device with tactile and proprioceptive feedback for spatial design tasks. 2017 IEEE International Symposium on Mixed and Augmented Reality (ISMAR-Adjunct); 2017, p. 223–228.

[40] Mohanty, R, Castillo, R, Ragan, E, Krishnamurthy, V. Investigating force feedback in mid-air sketching of multi-planar 3D curve-soups. Journal of Computing and Information Science in Engineering 2019;1–14 doi:10.1115/1.4045142.

[41] Wiese, E, Israel, J, Meyer, A Bongartz, S. Investigating the Learnability of Immersive Free-Hand Sketching. In: Proceedings of the Seventh Sketch-Based Interfaces and Modeling Symposium. SBIM '10; Eurographics Association; 2010, p. 135–142. URL: http://dx.doi.org/10.5555/1923363.1923387. doi:10.5555/1923363.1923387.