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Investigating User Requirements and Usability of Immersive Three-dimensional Sketching for Early Conceptual Design – Results from Expert Discussions and User Studies

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Abstract

As immersive 3-d user interfaces reach broader acceptance, their use as sketching media is attracting both commercial and academic research. So far little is known about user requirements and cognitive aspects of immersive 3-d sketching. Also its integration into the workflow of virtual product development is far from being solved.

In this paper we present results from two focus group expert discussions and a comparative user study on immersive 3-d sketching which we conducted among professional furniture designers. The results of the focus groups show a strong interest in using the three-dimensional space as a medium for conceptual design. Users expect it to provide new means for the sketching process, namely spatiality, one-to-one proportions, associations, and formability. Eight groups of functions required for 3-d sketching were generated during the discussions. The results from the user study show that both the sketching process and the resulting sketches differ in the 2-d and 3-d condition, namely in terms of the perceived fluency of sketch creation, of the perceived appropriateness for the task, of the perceived stimulation by the medium, movement speed, sketch sizes, details, functional aspects, and usage time. We argue that both 2-d and 3-d sketching are relevant for early conceptual design. As progress towards 3-d sketching, new tangible interactive tools are needed which account for the user's perceptual and cognitive abilities.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Line and Curve Generation); H5.2. Information interfaces and presentation (e.g., HCI): User Interfaces: Input devices and strategies.

1. Introduction

Whereas immersive three-dimensional (3-d) sketching is subject to academic research and industrial applications, only little is known about its real benefit compared to two-dimensional (2-d) sketching or other means of conceptual design such as physical modelling, use of CAD systems or even gesturing.

Sketches are usually the first visual product models that designers create by *externalising* their mental models and concepts of the product. But, as Suwa & Tversky [ST96; Tve03] point out, sketching is not only about externalising pre-existing mental models. Rather, designers develop their ideas while sketching and discover new links and approaches for new product features (reflecting-in-action [Sch83], Figure 1). During the product creation process, sketches are essential means in the product planning and task clarification phases (finding and choosing product ideas), the conceptual phase (concretising of principle solution variants) and the embodiment design phase (preliminary design, choosing proper variants, detail design) [PBFG05; PLDM04]. Sketching on paper is still the main form of sketching: 60 percent of all drawings made during product design are sketches [Bir94], 80 percent of the time spent for writing or tracing solutions is used for creating sketches [Dyl90] and the ratio of creation time compared to utilization is much higher for paper sketches (3:1) than for technical drawings (1:1) [EG95]. Sketches are used particularly frequently with CAD Systems [Röm02; Sta95]. The core properties of sketches according to Buxton [Bux07]

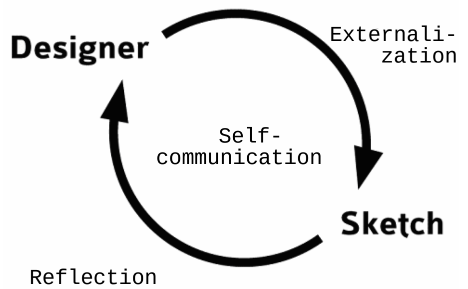

Figure 1: *Sketching as a process of externalization, reflection and self-communication.*

are that they are quickly and timely to create, inexpensive, disposable, plentiful, that they have a clear vocabulary, minimal detail, and that they are ambiguous and suggest and explore solutions rather than confirm them. Sketches do not necessarily have to be pen and paper drawings, they can also be collages or models [Hum00]. Physical means still supersede computers as sketching tools. This is usually ascribed to the delay and low resolution of the digital systems which slow down the self-communication process and hinder designers wishing to draw and think concurrently [Röm02; Sta95].

Sketching Properties	***Expert's statements***
Sketching Process	
A sketch is **quick**	"the hand is unbeatably fast"
Timely: A sketch can be provided when needed.	"pen and paper are a medium that is always on-hand"
Inexpensive: A sketch is cheap.	"you do not need expensive technology, paper is enough"
Sketches are **disposable**	*contradiction*: "I believe I have never thrown away a sketch in the past 30 years"
Sketching Results (Sketches)	
Plentiful: Sketches tend to not exist in isolation	"I create up to 30 sketches of one and the same thing"
Clear vocabulary: The style distinguish it from other types of renderings	"sketches are like notes"
Distinct Gesture: Not tight. Open. Free.	"sketches look 'different'"
Minimal Detail: Only include what is required	"sketches say more, if you remove detail"
Appropriate Degree of Refinement: Not beyond the level of the project being depicted.	"the sketch is not written out yet"
Suggest and explore rather than confirm	"sketches are thinking tools"
Sketches are intentionally **ambiguous**	"sketches contain the various possibilities which lay partly blurred in space"

Table 1: *Characteristic properties of sketches according to Buxton [Bux07, p. 110]*

2. 3-d sketching

If virtual environments are a new medium and as such very likely to influence the sketching process and sketches are a reflective means which not only represent but also generate knowledge about a product, then 3-d sketching should significantly alter the sketching process. 3-d visualization shows advantages for solving basic tasks [SJOC01]. Among other things, we expected 3-d sketches to be more appropriate for externalising visual mental models because they would allow designers to move within their drawing and because they would provide more cues for the self-communication process.

3-d sketching and drawing systems for immersive VR systems have become increasingly popular. Some systems use plain hand gestures as "input" (e.g.[Hum00; SPS01]), others employ free-hand tools for the generation of visual rich and aesthetic sketches and paintings (e.g. [KAML*01; MI04]) or provide haptic-aided input techniques and rich controllable interaction for refined 3-d illustration [KZL07]. Other solutions focus on the creation of advanced CAD-like free-form curves and surfaces (e.g.[FASM02]) or generate exact surfaces and solid geometries by automatically recognizing basic object patterns from hand drawn sketches ([DML04; Mül07; PL03]). Hybrid solutions which seamlessly integrate two-dimensional input on LCD touch-screens and 3-d visualization on auto-stereoscopic desktop screens have been shown to enable fluent creative sketching [TKNK*03].

3. Focus group expert discussion

In an effort to investigate potentials and limitations of 3-d sketching in immersive virtual environments for conceptual design, in order to investigate whether 3-d virtual space is an adequate and supporting sketching medium, and in order to derive user requirements towards functionality and tools of such systems, we choose a qualitative research approach.

In five individual interviews with design experts we investigated the field of product design and sketching and created a semi-structured guideline which included open research questions to be addressed in follow-up focus group interviews. (See [KC00] for a description of focus groups and [RHMM03] for an example.)

3.1 Subjects

We conducted two focus group interviews among 14 design experts who were selected by selective sampling from the fields of furniture design and interior design. This area was chosen because in this domain shape-defining product models, which might benefit most from 3-d sketching, bear most of the product characteristics and sketches are the major design tools during the early conceptual phases. Among the participants were university professors (3), interior designers (3), architects (3), product designers (3) and mechanical engineers (2) with an average professional experience of 11.6 years. Participants received a refund for their expenses.

3.2 Procedure

Both focus group sessions were led by two moderators who had little influence on the content of the discussion but intervened whenever it was about to loose focus. The sessions lasted 2.5 hours and were videotaped, the co-moderator took a handwritten protocol. Prior to the expert focus groups we conducted two test sessions with design students and post-graduates in order to elaborate our moderation skills and the guideline.

After a short introduction, participants answered and discussed questions related to "sketching and furniture design". In this starting phase, each expert had enough time to introduce his or her individual design approach. Questions then addressed the tasks in early phases of product design, the functionality of sketching and sketches, and the use of tools. A video collage of 3-d furniture sketching was then shown as a stimulus [Fro07]. Questions following the video session addressed possibilities and limitations of 3-d sketching and differences and commonalities of 2-d and 3-d sketching. At the end of both focus group sessions, participants were asked to summarize their ideas and to name and write down their favourite 3-d sketching functions on cards. These were put on pin boards and grouped into function-clusters in a joint discursive process guided by the two moderators.

3.3 Analysis

Owing to the fact that the same guideline was used in both focus groups, results could be aggregated into a combined result. Both the written protocols and the functions clusters were carefully analyzed, aggregated, structured and interpreted and finally discussed among both moderators in order to find a common notion on the content and answers to the main research questions [May83]. Thus, the results reflect both the ideas developed during the verbal discussion and the functions written on the cards.

3.4 Results

Most of the participants appreciated the potential benefits of 3-d sketching for their domain. Some initial scepticism ("you don't need expensive technology, paper is enough") diversified during the discussion and was often not present anymore at the end of the discussion ("three-dimensional sketching would be impressive", "I would immediately buy it"). The key advantages of immersive 3-d sketching compared to traditional sketching methods expressed and desired by the participants were:

- **Spatiality:** The possibility "to work with the space"

- **One-to-one proportionality:** The possibility to draw models "one-to-one". This feature was emphasized compared to CAD systems, "where you often see what it looks like only after it is finished"

- **Associations**: The possibility to "take existing objects into the virtual space and work with them"

- **Formability**: The possibility to manually form virtual sketches

By analyzing the functions given at the end of the focus group by the experts, we found the function groups seen in Table 2. They can be categorized into classical drawing and modelling techniques, techniques known from CAD, and entirely new techniques which would be unique to immersive environments.

The content analysis of the focus group protocol revealed that the participants' concept of sketching contains all sketch properties named by Buxton [Bux07] (Table 1). Only in respect to the property "disposable" we found contradictions. Participants often called their sketches "personal", "private" or "intimate" which even "after ten years" would reveal "what was the intention in it".

Function	Example
Classic drawing techniques	drawing, erasing
Classic modelling techniques	removing, applying
Classic CAD modelling techniques	creating and manipulating geometric primitives, scaling, mirroring, cutting, copying
New 3-d drawing techniques	copying of real objects, undo Function, virtual drawing, patterns of all kinds
New 3-d modelling techniques	compressing, dragging, pushing, folding, stretching
Abstraction techniques	overlaying models, introducing inaccuracies, transparency
Dynamics	history slider, storing the creative process, displaying traces of usage and processes
Environmental conditions	body proportions, incorporate context, create creative environments

Table 2: *List of required functions which should be provided by 3-d sketching tools.*

Regarding the limitations, participants expected that sketching on paper is not going to be replaced by digital media, but, rather it will coexist. This replicates prior findings, e.g. in [Röm02; Sta95]. Also materiality and physical support was missed ("you can't draw a perfect circle in space", "there are too many degrees of freedom", "finding points in space is difficult").

Both primary sketching functions, to support human memory (externalization) and to aid the self-communication process were constantly mentioned ("I have the picture in mind or I try to form the various possibilities").

3.5 Conclusions

The participants' opinion towards 3-d sketching can be summarized as:

- The majority expect high benefits for their work from using 3-d sketching.
- The topic has a positive emotional connotation.
- Sketching on paper will not be replaced.
- The major sketching function (memory support, externalization aid) and sketch properties (Table 1) known from traditional sketching are also attributed to 3-d sketching with only minor modifications.

4. Comparative sketching study

In an effort to systematically investigate the effects of using 3-d space as a sketching medium, we conducted a comparative user study among 24 furniture designers and interior architects and let them perform several sketching tasks in the field of furniture design.

4.1 Hypotheses

Our study has been intended to test the following three hypotheses (see the remarks on the 'quasi-2d' condition in the discussion below):

1) Sketching in 3-d space allows better and more direct externalisation of mental images than 2-d sketching because it does not require mental and manual projection onto 2-d planes (e.g. paper).
2) 2-d and 3-d space are different media. Using them as a sketching medium generates qualitatively different *sketches* in terms of creativity and functional principles of the sketched object (product), and in terms of creativity, aesthetics, and abstraction levels of the sketch (drawing).
3) The sketching and solution finding *process* is also altered by changing the sketching medium.

4.2 The experiments

4.2.1 Interaction techniques

The study was set up in a VR-Cave, an immersive VR environment with five back projected walls. Both user and interaction devices were tracked by means of magnetic tracking (Ascension MotionStar). Tracking data was smoothed in order to reduce noise and allow drawing of straight lines by hand.

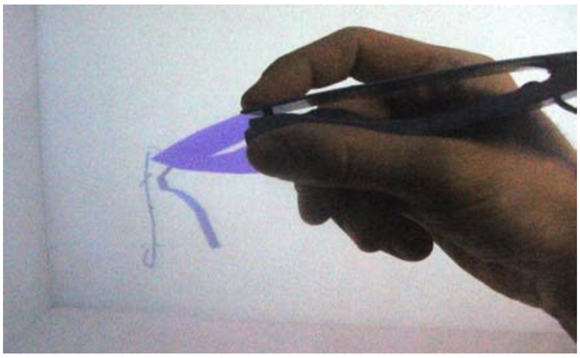

Figure 2: *Hybrid pen for 3-d sketching*

The 3-d sketching prototype we developed for our study employed a line based sketching and an undo / history functionality. We chose a pen as interaction device (Figure 2) in order to keep the results of the study comparable to 2-d sketching on paper. Drawing with virtual ink was possible by gently pressing the upper bow of the pen until it touched the lower bow. This relates to the habit of putting a pen on paper, but here the passive touch feedback which originally came from the medium is now generated within the tool. This lets the user experience drawing and resistance as a single percept and creates the impression of using a graspable medium. After a pre-test with three users we found a hybrid pen version most appropriate for the task, compared to entirely physical or virtual pens. The virtual ink was drawn at the tip of the hybrid pen directly into the virtual environment, following the movements of the pen (and the user's hand). The width of the virtual ink in the form of a plain blue band was scaled from 1 to 8 mm according to the force by which the user pressed the upper bow (the force was measured by means of a sensor from Phidgets Toolkit [Phi07]). Releasing the upper bow of the pen also stopped the drawing.

A simple slider device allowed both sequentially undoing strokes and replaying the creation process of the sketch.

In the 3-d condition, participants were allowed to use the whole 3-d space available in the cave (2.5 m^3) for their sketches. In the 2-d condition, participants were told both in written form and verbally to draw onto an imaginary wall or paper in the centre of the Cube (2.5 m^2). They were informed that the system would not restrict them and that it was their own responsibility to draw two-dimensionally.

We intentionally decided to design the 2-d sketching task in the same technical environment as the 3-d task, and provided no analogue paper wall or transparent sketching pane inside the Cave for the following reasons:

Technical reasons: We wanted to keep the inferring variables constant between both conditions, namely calibration errors, system update rate, restricted field of view, visual resolution and clarity, luminance and contrast, occlusions between user, sketch and tools, infinite depth of field, absence of accommodation, accommodation-vergence conflict, accommodation mismatch, etc. [DM96]

User related reasons: We intended to prevent users from applying their pre-existing sketching skills in the 2-d task; we rather intended to have an unusual setting which required a considerable learning effort in both conditions.

4.2.2 Questionnaires and protocols

Prior to each experiment, users had to fill out a questionnaire surveying personal information as well as personal sketching experience, experience with VR, 3-d Environments and CAD software. After each task, users had to answer two questionnaires concerning 1) the sketching experience and 2) hedonic and pragmatic qualities of the interaction techniques. The aim of the first, self-developed questionnaire was to measure user satisfaction, perceived unity of interaction objects, task difficulty, perceived properties of the sketching process (Table 1), and whether it was utilized as memory support and externalization aid. Secondly, we employed the AttrakDiff of Hassenzahl [Has04; HBK03]. This questionnaire goes beyond standard usability questionnaires in that it not only measures user-perceived usability in terms of *pragmatic* functional quality (PQ). It also provides means for measuring *hedonic* attributes of interactive products, namely *stimulation* by the product (HQ-S) and *identification* with the product (HQ-I), and the product's *attractivity* (ATT). *Stimulation* is related to the human need for developing his or her personality and for gaining new skills and knowledge. *Identification* stands for the users' need to express themselves through objects and to communicate their own personality to others, e.g. by certain products. These human needs and wishes are important for the overall user experience of a product, or, as in our case, of interaction techniques. The AttrakDiff questionnaire consists of 7-point items with bipolar verbal anchors (i.e., a semantic differential) for each attribute group. The independence of the attribute groups was shown by means of a factor analysis [HBK03]. A semantic differential is a commonly used type of a rating scale, it is assumed to have interval scale properties and may be analyzed by parametric tests [BHP66; BD06, p. 180f]. At the end of each experiment we also tested for spatial ability [Git90].

We also developed an evaluation sheet for ourselves in order to compare the quality of the sketches after the study, namely creative value based on the visual elements used (similar to [UJ95]), the abstraction level (visual-graphical, schematical, symbolical, verbal [Pac05]), the one-to-one proportionality, the number of solution variants and number of sketches per task. Other aspects such as overall quality, creativity, and aesthetics of the sketch, sketch style and associative power were subject to a review by an academic expert with thirty years of technical sketching experience.

During all experiments, a mediator took written records of important events and verbal comments. A log-file was automatically written for each trial in order to measure the participants' behaviour, e.g. overall sketching time, pen usage time, movement speed, and sketch volume.

4.3 Subjects

We recruited 24 subjects (18 male, 5 female, mean age 33, *SD*=7.05) by means of e-mail invitations among furniture designers and interior architects from design offices and universities. 15 participants were professionals with on average 8.43 years of working experience (*SD*=6.12). Six subjects were students who spent an average 3.33 years at university (*SD*=1.63). Three subjects did not answer the related questions (missing data).

4.4 2-d and 3-d sketching tasks

In both conditions the task was to sketch furniture that would be installed in the entrance hall of the Institute for Machine Tools and Factory Management IWF of the Technical University Berlin. The first task was to sketch a suspended table which could be pushed up towards and pulled down from the ceiling whenever needed. The second task was to sketch a bar for the entrance hall to be used during receptions. The bar should be lockable and appear unobtrusive when not in use. The candidates tackled the tasks in the same order, but the sequence of the interaction techniques, namely 2-d and 3-d sketching, was varied (Figure 3, Figure 4, and Figure 5). Prior to the tasks, participants underwent a training phase in which they were told to draw primitive objects in 3-d space in order to get familiar with the interaction technique. The training time was not limited and lasted 5 minutes on average.

Figure 5: *Participant sketching a suspended table (2–d).*

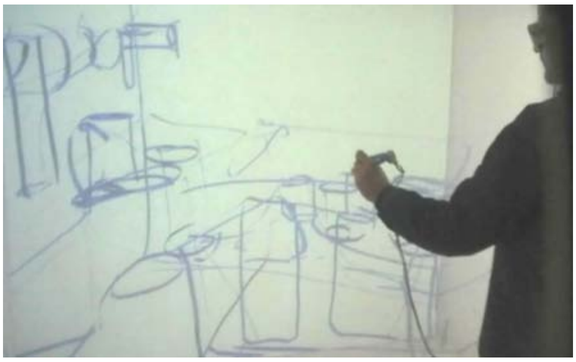

Figure 5: *Participant sketching a bar (3-d).*

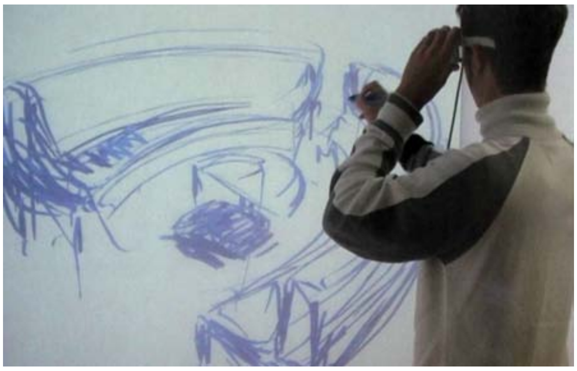

Figure 5: *Participant sketching a bar (3-d).*

4.5 Results

4.5.1 User-perceived attributes

Analyzing the results of the 7-point scale AttrakDiff questionnaire by means of t-tests shows significant preferences of the participants in all dimensions (Figure 6). In the hedonic quality identification (HQ-I), 3-d sketching is ranked significantly higher than 2-d sketching (M_{3D}=4.55, SD_{3D}=.84; M_{2D}=3.70, SD_{2D}=1.13) t=-3.33, p<.001. This applies also to the hedonic quality simulation (HQ-S; M_{3D}=5.94, SD_{3D}=.58; M_{2D}=5.14, SD_{2D}=1.32) t=-3.14, p<.001, and also to the pragmatic quality (PQ; M_{3D}=4.18, SD_{3D}=1.23; M_{2D}=3.58, SD_{2D}=1.16) t=-2.25, p<.05. Finally, also the overall attractivity (ATT) of 3-d sketching

(M_{3D}=5.16, SD_{3D}=.95) was perceived significantly higher than of 2-d sketching (M_{2D}=4.17, SD_{2D}=1.28) t=-3.94, p<.001.

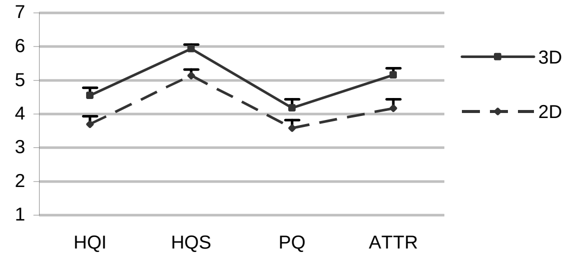

Figure 6: *Results of the AttrakDiff questionnaire for 2-d and 3-d sketching techniques.*

The answers to the post questionnaire with a 5-point scale revealed differences in the participants' attitude towards both sketching techniques and media. The sketching key functions 'externalization' ($Median_{3D}$=3, IQR_{3D}=2.25–4.00; $Median_{2D}$=2, IQR_{2D}=1.25–3.00) Z=-2.573, p<.01, and 'self-communication' ($Median_{3D}$=3.67, IQR_{3D}=2.33–4.00; $Median_{2D}$=2.50, IQR_{2D}=2.00 – 3.00) Z=-2.562, p<.01, were both rated higher for 3-d than 2-d sketching. Participants also answered that they could realize their ideas faster with 3-d than 2-d sketching ($Median_{3D}$=3.00, IQR_{3D}=2.25–4.00; $Median_{2D}$=2.00, IQR_{2D}=1.00–3.00) Z=-2.790, p<.005 (based on Wilcoxin test). An item in respect of fluency of the sketching process almost reached significance level towards a higher value for 3-d sketching ($Median_{3D}$=2.50, IQR_{3D}=2.00–4.00; $Median_{2D}$=2.00, IQR_{2D}=2.00–3.00) Z= -1.615, p<.106). Also all items related to Buxton's attributes failed to reach significance level.

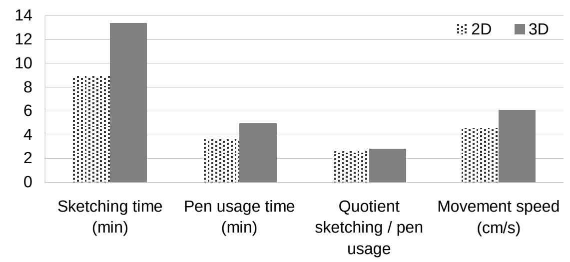

Figure 7: *Sketching and pen usage time, speed.*

4.5.2 Measured user behaviour

Participants moved 33 percent faster in the 3-d condition than in the 2-d one (M_{3D}=.061 m/s, SD_{3D}=.019; M_{2D}=.046 m/s, SD_{2D}=.031) t=-2.25, p<.035. The average time for creating a 3-d sketch was 50 percent longer than for 2-d ones (M_{3D}=13.38 min, SD_{3D}=5.54; M_{2D}=8.97 min, SD_{2D}=5.26) t=-3.88, p<.001. The time in which participants used (pressed) the pen for creating sketches was 37 percent longer in the 3-d than in the 2-d condition (M_{3D}=4.96 min, SD_{3D}=2.17; M_{2D}=3.64 min, SD_{2D}=2.56) t=-3.88, p<.001. But the quotient between overall sketching time (includes reflection / self communication time) and pen usage time (includes only externalization time) was almost the same (M_{3D}=2.81, SD_{3D}=.74; M_{2D}=2.63, SD_{2D}=.90).

4.5.3 Sketch quality, measures and expert's ratings

The appearance of the sketches varied strongly from very aesthetic sketches to scribbles which were hard to recognize. Some examples are shown in Figure 3, Figure 4, Figure 5, and Figure 9. Neither our post study evaluation sheet nor the expert's review revealed significant differences between the conditions. Only the one-to-one proportionality almost reached significance level in a McNemar test (p=.109). It was found in sketches by nine subjects in the 3-d condition and three subjects in the 2-d condition.

For each sketch we calculated the smallest enclosing bounding box. We found the volume five times bigger for 3-d sketches (M_{3D}=1.64 m^3, SD_{3D}=1.65; M_{2D}=.34 m^3, SD_{2D}=.45) t=-4.20, p<.0001 (Figure 8). We also compared the sizes of the sketches' largest sides. Also in this comparison 3-d sketches were twice as large as 2-d ones (M_{3D}=1.50 m^2, SD_{3D}=.98; M_{2D}=.67 m^2, SD_{2D}=.49) t=-4.83, p<.0001. Finally, the exported VRML files contained twice as many points (details) for 3-d sketches than for 2-d sketches (M_{3D}=4318, SD_{3D}=2628; M_{2D}=2399, SD_{2D}=1625) t=-3.15, p<.005.

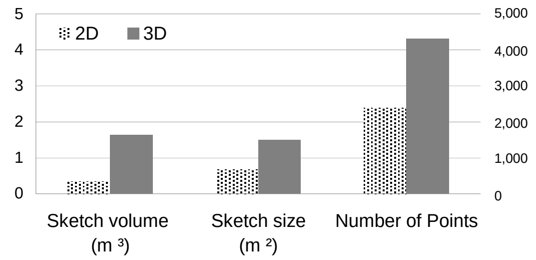

Figure 8: *Sketch volume, size and number of points.*

4.5.4 Observed user's behaviour

We also found that eight out of 24 participants incorporated 3-d elements in their 2-d sketches; four of them in task one, the other four in task two. Most of them noticed this and commented verbally, e.g. "I am always sliding into 3D" or "I can't think two-dimensionally anymore". The 3-d elements were mostly surfaces and panes expanding into the z-dimension (Figure 9).

Among the most prominent benefits of 3-d sketching mentioned in the post-trial questionnaires, participants mentioned the one-to-one scale (repeating the results from the focus group) and the possibility to interact with the sketch. Paper and pen were provided during the experiment, but only one participant created paper sketches prior to sketching in three dimension.

The observation revealed a very interactive behaviour for many subjects during the 3-d sketching task. We regularly observed designers who tried to sit down in their sketches, who looked below sketched tables or walked around and looked at their sketch from different perspectives. Most of the participants were very agile while sketching. Sketching and moving was an interwoven process.

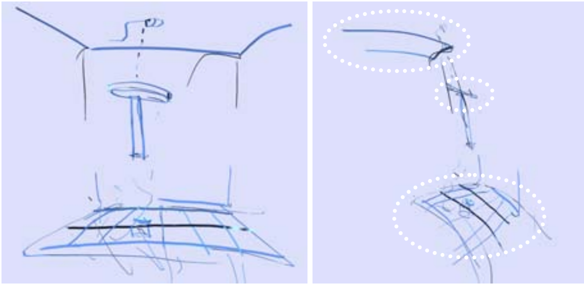

Figure 9: *Front and side view of a sketch of a hanging table in the 2-d condition (task one). 3-d elements are marked white in the side view.*

In respect to the pen used, users often complained about an offset between the physical and virtual parts of the pen and also about the delay, which was up to 200ms and was caused by both the tracking equipment and the smoothening algorithm.

4.6 Discussion

With respect to our second hypothesis, the results show no clear benefit of 3-d sketching compared to 2-d sketching in terms of creativity, aesthetics, overall quality, abstraction levels, etc. It can even be said that 2-d sketching is more efficient, because the 2-d sketches were created faster and were not in any significant way rated differently in both our post study evaluation and the expert's rating.

However, we get a different picture if we weight the opinions of the 24 study participants higher than the opinion of the one expert. Taking the subjective pragmatic quality as a measure of both the sketching process and the satisfaction of the participants with their sketches, we could see 3-d sketching as a creative design method. The interactive behaviour of the participants during the study, e.g. to sit down in sketched chairs and walk in virtual bars, is another indicator that the creative process gains new degrees of freedom in 3-d sketching.

User ratings suggest that the sketching process differs in externalizing speed and fluency in favour of the 3-d condition. In contrast, the quotient between overall sketching time and pen usage time was almost the same in both conditions, which means that participants sketched (externalized) and reviewed (reflected) their sketches with the same ratio. This is an indicator that the self-communication process is similar in both conditions, but, probably also due to the higher stimulation, this lasts longer in the 3-d condition. As a result, 3-d sketches contain more details – a feature usually needed in later phases of conceptual design.

Further support for our first hypothesis comes from the findings about using 3-d elements also in the 2-d condition. It is to assume that designers think, memorize and externalise (by moving their hands) mental sketches originally in three dimensions and that 3-d space is thus the proper medium for creative solution finding. Further studies should investigate whether this phenomenon is due to the experimental setting or the influence of the training at the beginning of each experiment.

After reviewing the results of the user study we questioned to some extent our initial decisions in respect to designing the 'quasi-2-d' condition under the same technical conditions as the 3-d task. Further studies might involve four conditions, namely drawing on paper walls of the same size as the back pane of the Cave environment, sketching two-dimensionally on a transparent physical pane in the Cave's centre, and our two conditions, 2-d and 3-d sketching "in the air", without physical supporting area. This design could reveal in more detail which factors support the creative sketching process, especially physical resistance (support), visual aspects such as resolution, contrast, and time related aspects, e.g. lag and update rate. Comparing real 2d-paper sketching with "sketching in the air" could also reveal differences in the elements used in the sketches, namely visual-graphical, schematical, symbolical, and verbal elements [JGD02; Pac05], for which we could find no differences in our study.

The results suggest that designers "accept" 3-d sketching as a medium for expressing and developing design variants and solutions. Many of the participants were very enthusiastically about the new sketching possibilities. One participant said: "I have been sketching since I was fifteen. If I had been learning such a technique since then, how good would I be today!" Even if our 2-d condition can hardly be compared with sketching on paper, we can say that under the same technical conditions, 3-d sketching is the preferred interaction technique for sketching in space. The results from the AttrakDiff questionnaire support that claim. Not only could designers identify themselves more with 3-d than with 2-d sketching and felt more stimulated by the former, which could be explained with the novelty of the technology, they also rated the pragmatic, solution related quality higher for 3-d than for 2-d sketching. This adds support for our hypotheses 1, 2, and 3.

5. Conclusion and outlook

Due to the strong interest we received from the design community and the presented results of our study we are optimistic that 3-d sketching has the potential to develop towards a new tool that supports creative work and extends the human understanding of the expressive potential in digital space. Some expectations from the focus group could be met in the user study, e.g. the use of proportional one-to-one sketches, the stimulating effect of 3-d sketching and its novelty. Other aspects, e.g. formability of the sketch could not be evaluated due to lacking functionality of our prototype.

From the literature (e.g. [DML04]), as well as from our focus group and the comments of the participants of the study we know that the line-based sketching approach is not sufficient for 3-d sketching. Thus we developed a tangible two-handed Bezier tool and a free-form extrusion tool which can be controlled entirely by direct physical manipulation and without issuing commands. They will be subject of further studies. In order to increase usability, further research is needed e.g. in the field of reduction of tracking induced time-lag, for example by means of Kalman filters, and the reduction of noise caused by the tracking system which prevents the drawing of smooth lines and shapes.

The results from both the focus groups and our user study could contribute some evidence to the benefits of 3-d sketching and its specific features in the design process. Nevertheless, in order to find application fields and to legitimate the expansive equipment, further, more specific research should go into working systems in real industrial environments that integrate, organizationally and technically, into the virtual product creation process.

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