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Sketch-Based Interfaces

Investigating three-dimensional sketching for early conceptual design—Results from expert discussions and user studies

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ABSTRACT

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

We present results from two focus group expert discussions, a comparative user study on immersive 3D sketching conducted among professional furniture designers and a qualitative content analysis of user statements. The results of the focus group discussions show a strong interest in using the three-dimensional (3D) 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 3D sketching were outlined during the discussions.

The comparative study was intended to find and investigate advantages of immersive three-dimensional space and its additional degrees-of-freedom for creative/reflective externalization processes. We compared a 3D and a 2D baseline condition in the same technical environment, a VR-Cave system. In both conditions, no haptic feedback was provided and the 2D condition was not intended to simulate traditional 2D sketching (on paper). The results from our user study show that both the sketching process and the resulting sketches differ in the 2D and 3D condition, namely in terms of the perceived fluency of sketch creation, in terms of the perceived appropriateness for the task, and in terms of the perceived stimulation by the medium, the movement speed, the sketch sizes, the degree of detail, the functional aspects, and the usage time. In order to validate the results of the focus group discussions, we produced a questionnaire to check for the subjectively perceived advantages and disadvantages in both the 2D and 3D conditions. A qualitative content analysis of the user statements revealed that the biggest advantage of 3D sketching lies in the sketching process itself. In particular, the participants emphasized the system's ability to foster inspiration and to improve the recognition of spatiality and spatial thinking.

We argue that both 2D and 3D sketching are relevant for early conceptual design. As we progress towards 3D sketching, new tangible interactive tools are needed, which account for the user's perceptual and cognitive abilities.

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1. Introduction

Whereas immersive three-dimensional (3D) sketching is subject to academic research and industrial applications, little is known about its real benefit compared to two-dimensional (2D) sketching or other means of conceptual design such as physical modelling, the use of CAD systems or even gesturing [1].

Sketches are usually the first visual product models that designers create by *externalizing* their mental models and concepts of the product. But, as Suwa and Tversky [2,3] point out, sketching is not only about externalizing pre-existing mental models. Rather, designers develop their ideas while sketching and discover new links and approaches for new product features (reflecting-in-action [4], Fig. 1). During the product creation process, sketches are essential in the product planning and task clarification phases (finding and choosing product ideas), the conceptual phase (specifying principal options) and the embodiment design phase (preliminary design, choosing proper variants, detailed design) [5,6]. Besides CAD models, sketches on paper are still the most important product models in early design

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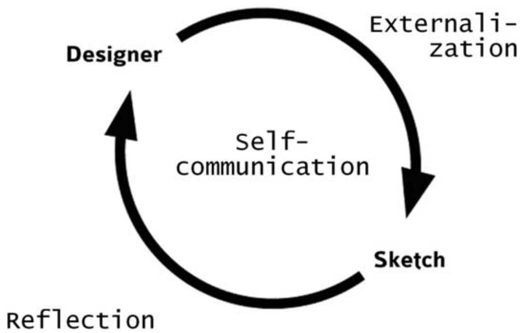

Fig. 1. Sketching as a process of externalization, reflection and self-communication.

phases: 60 percent of all drawings made during product design are sketches [7], 80 percent of the time spent writing or tracing solutions is used for creating sketches [8] and the ratio of creation time compared to utilization is much higher for paper sketches (3:1) than for technical drawings (1:1) [9]. In a study with 66 designers and engineers, Römer [10] found that sketches are used particularly frequently with CAD systems. In the studies, almost all participants utilized sketches in early design phases. Sketching on paper seems to offer functionalities that cannot be provided by CAD systems, e.g. externalization speed, high visual resolution, and instant visual feedback.

The core properties of sketches according to Buxton [11] are that they are quick, inexpensive, disposable, plentiful, that they have a clear vocabulary, minimal detail, and that they are ambiguous and suggest as well as explore solutions rather than confirm them. In comparison, physical tools are more widely used and relevant than digital ones. 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 [10,12].

2. 3D sketching

In reflective self-communication processes such as sketching, the actual medium determines many of the properties and affordances an external image or model provides. Virtual environments are a new medium and as such are very likely to influence the sketching process. 3D visualizations, for example, have advantages for solving basic tasks [13]. For various reasons we expected an immersive 3D medium to be more appropriate for externalizing visual mental models than a 2D medium would be. For example, 3D environments would allow designers to move within their drawing, they would not require mental projection of 3D product models onto 2D planes and they could provide more cues for the self-communication process.

3D sketching and drawing systems for immersive VR systems have become increasingly popular. Some systems use plain hand gestures as "input" (e.g. [1,14]), some employ freehand tools for the generation of visually rich and aesthetic sketches and paintings (e.g. [15,16]). Other solutions focus on the creation of advanced CAD-like free-form curves and surfaces (e.g. [17]) or generate exact surfaces and solid geometries by automatically recognizing basic object patterns from hand-drawn sketches [18–20]. Hybrid solutions, which seamlessly integrate two-dimensional input on LCD touch-screens and 3D visualization on auto-stereoscopic desktop screens, have been shown to enable fluent creative sketching [21].

Much research was done in the area of haptic-aided input techniques for immersive sketching and modelling. In a study with industrial designers, Sener et al. [22] found that physical feedback is helpful for understanding the form and texture qualities of virtual objects during immersive modelling tasks. Raymaekers et al. [23] utilized haptic feedback for controlling the width of sketched curves and for providing editing and erasing functions. In a comparative study, Keefe et al. [24] investigated the effects of haptic support in one- and two-handed 3D sketching modes. They found that interaction techniques that simulate tape-like or slowed drawing (drag) help to improve the accuracy of 3D drawings, but require longer sketching times (speed-accuracy trade-off). Keefe et al. found also that augmenting freehand drawing with simple haptic friction effects does not considerably improve sketch quality.

3. Focus group expert discussion

In an effort to investigate the potentials and limitations of 3D sketching in immersive virtual environments for conceptual design, i.e. whether 3D virtual space is an adequate and supporting sketching medium, and in order to derive user requirements regarding functionality of and tools for such systems, we chose 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 [25] for a description of the focus groups and [26] for an example).

3.1. Subjects

We conducted two focus group interviews among 14 design experts from the fields of furniture design and interior design. Their shape-defining product models, which might benefit most from 3D sketching, bear most of the product characteristics. Sketches are the major design tools during the early conceptual phases. Taking part were three university professors, three interior designers, three architects, three product designers and two mechanical engineers, with an average of 11.6 years professional experience. Participants received an expense allowance.

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 lose focus. The sessions lasted 2.5 h and were videotaped, one moderator took hand-written minutes. Prior to the expert focus group interviews the moderators conducted two test sessions with design students and post-graduates in order to develop moderation skills and the guidelines.

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 own 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 3D furniture sketching was then shown as a stimulus [27]. Questions following the video session addressed possibilities and limitations of 3D sketching and differences as well as commonalities of 2D and 3D sketching. At the end of both focus group sessions, participants were asked to summarize their ideas and to write down their favourite 3D sketching functions on cards. These were put on pin

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boards and grouped into function-clusters in a joint discursive process guided by the two moderators.

3.3. Analysis

The same guidelines were used in both focus groups, so results could be aggregated into a combined result. The notes and the function-clusters were carefully analyzed, aggregated, and interpreted and finally discussed by the moderators in order to find a common notion on the contents and answers to the main research questions [28]. 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 3D sketching for their domain. Initial scepticism (“you don’t need expensive technology, paper is enough’’) had dwindled by the end of the discussion (“three-dimensional sketching would be impressive”, “I would immediately buy it’’). The key advantages of immersive 3D sketching compared to traditional sketching methods expressed and desired by the participants were as follows:

- *Spatiality*: The possibility “to work with the space”, to create spatial models and to perceive their spatial impact. 3D sketching would allow to “walk-in” models and could “raise the communication to a higher level”.
- *One-to-one proportionality*: The possibility to draw models “one-to-one”, e.g. in the proper proportions in relation to the own body or in relation to other pieces of furniture. This feature was emphasized when 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”, for example, to “walk into a restaurant and to sketch pieces of furniture there”; or using “object libraries” which make it possible to “load” pre-defined models into the sketching environment for further refinement.
- *Formability*: The possibility to manually warp virtual sketches, which in turn allows for a gradual developing and testing of ideas until they are “mature”.

By analyzing the functions given at the end of the focus group interviews by the experts, we found the function groups as given in Table 2. They can be categorized into classical drawing and modelling techniques, techniques known from CAD, and entirely new techniques that 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 [11] (Table 1). We only found contradictions with respect to the property “disposable”. Participants often called their sketches “personal”, “private” or “intimate”, which even “after ten years” would reveal “what was the intention in it”.

Regarding the limitations, participants expected that sketching on paper is not going to be replaced by digital media, but that the two will coexist. This replicates prior findings, e.g. in [10,12]. 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, i.e. to support the human memory (externalization) and to aid the self-communication process, were consistently mentioned (“I have the picture in mind or I try to form the various possibilities”).

Table 1
Characteristic properties of sketches according to Buxton [11, p. 110].

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 at 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 not to 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 yet fully formulated”
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 2
List of functions required from 3D sketching tools.

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 3D drawing techniques	Copying of real objects, undo function, virtual drawing, patterns of all kinds
New 3D 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

3.5. Conclusions

The participants’ opinion towards 3D sketching can be summarized as follows:

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

4. Comparative sketching study

In an effort to systematically investigate the effects of using a 3D space as a sketching medium, we further conducted a

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comparative user study among 24 furniture designers and interior architects. Participants were asked to perform several sketching tasks in the field of furniture design.

4.1. Hypotheses

Our study was intended to test the following three hypotheses (see the remarks on the "quasi-2D" condition in the discussion below):

(1) Sketching in a 3D space allows better and more direct externalization of mental images than sketching onto a 2D plane, because it does not require mental and manual projection onto 2D planes (e.g. paper).
(2) 2D and 3D spaces are different media. Using them as a sketching medium generates qualitatively different *sketches* with respect to creativity and functional principles of the sketched object (product), and with respect to creativity, aesthetics, and abstraction levels of the sketch (drawing) as such.
(3) The sketching and solution-finding *process* is also influenced by the choice of 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 rear-projected walls. Both the user and the interaction devices were tracked using a magnetic tracking method (Ascension MotionStar). The tracking data were smoothened in order to reduce noise and to allow the drawing of straight lines by hand.

The 3D sketching prototype that we developed for our study employed a line-based sketching and an undo/history functionality. We chose a pen as the interaction device (Fig. 2) in order to keep similarities to 2D sketching on paper. Drawing with virtual ink was possible by gently pressing an upper component of the pen until it touched the lower components. This relates to putting a pen on paper, but here the passive touch feedback is generated within the tool. The user experiences drawing and resistance as a single percept and hence gets 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 from 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 component (the force was measured with a sensor from Phidgets Toolkit [29]). Releasing the upper component of the pen stopped the drawing.

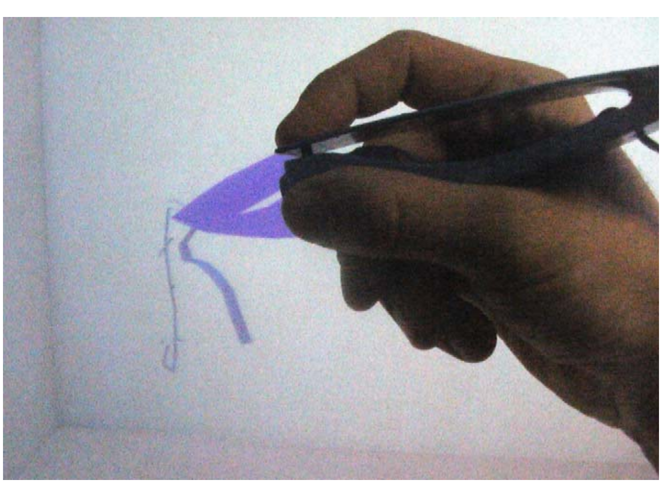

Fig. 2. Hybrid pen for 3D sketching.

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

In both conditions, participants were provided with regular paper and pencil in addition to the opportunities given by the virtual sketching environment. The aim was to check whether people would use conventional sketching techniques prior to sketching in three dimensions or in addition to it.

In the 3D condition, participants were allowed to use the whole 3D space available in the Cave (2.5 m^3) for their sketches. In the 2D condition, participants were told both in written form and verbally to draw onto an imaginary wall or paper in the centre of the Cave (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 chose to design the 2D condition in the same technical environment as the 3D condition, and provided no analogue paper wall or transparent sketching pane inside the Cave for the following reasons.

Technical reasons: We wanted to keep the confounding 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. [30].

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

User-related reasons/attention: As our research interest was about the spatial degrees of freedom (DOF), we did not add haptic support in the 2D condition. The sensorimotor coordination of three spatial degrees of freedom requires without doubt more attentional resources than of two DOF. Thus providing haptic support in the 2D condition would free attentional resources, which could then be allocated to the task (the overall problem). By providing haptic support we would have distorted our results, making it difficult or even impossible to attribute them to the haptic support or the varying spatial degree of freedom.

4.2.2. Questionnaires and protocols

Prior to each experiment, users had to give personal information and details of personal information as well as personal sketching experience, experience with VR, 3D 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. For the second questionnaire we used the AttrakDiff of Hassenzahl [31,32]. This questionnaire goes beyond standard usability questionnaires in that it not only measures user-perceived usability in terms of *pragmatic* functional quality (PQ) but also provides means for measuring *hedonic* attributes of interactive products, namely *stimulation* by the product (HQ-S) and *identification* with the product (HQ-I) as well as the product's *attraction* (ATT). *Stimulation* is related to the human need to develop personality and gaining new skills and knowledge. *Identification* stands for the users' need to express themselves

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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 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 [32]. 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 [33, p.180f, 34]. At the end of each experiment we also tested for spatial ability [35].

We developed an evaluation sheet in order to compare the quality of the sketches after the study in terms of perspective character and creative value based on the visual elements used (similar to [36]), the abstraction level (visual-graphical, schematic, symbolical, verbal [37]), the one-to-one proportionality, the number of solution variants, and the 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 30 years of technical drawing experience.

To minimize the influence of confounding factors on the results of our behavioural study (e.g. Hawthorne effect), the experimental tasks were presented without any preference towards 2D or 3D condition. Also, both conditions were presented in the same technical environment; so the novelty of the system should not have had any influence.

During all experiments, a mediator noted 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 (19 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. Fifteen participants were professionals with on average 8.43 years of working experience ($SD = 6.12$). Six subjects were students who had spent an average 3.33 years at university ($SD = 1.63$). Three subjects did not answer the related questions (missing data).

4.4. Sketching tasks

In both conditions the task was to sketch furniture for 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 that could be pushed up 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 2D and 3D, was varied (Figs. 3–5). Prior to the tasks, participants underwent a training phase in which they were told to draw primitive objects in 3D space in order to become familiar with the interaction technique. The training time, which was not limited, lasted 5 min on average.

Fig. 3. Participant sketching a suspended table (2D).

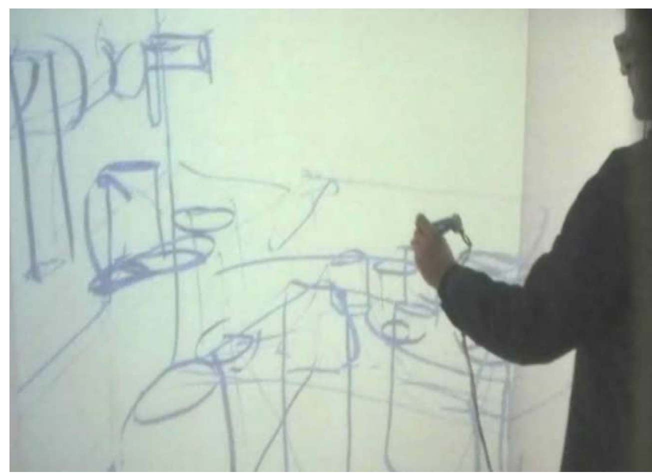

Fig. 4. Participant sketching a bar (3D).

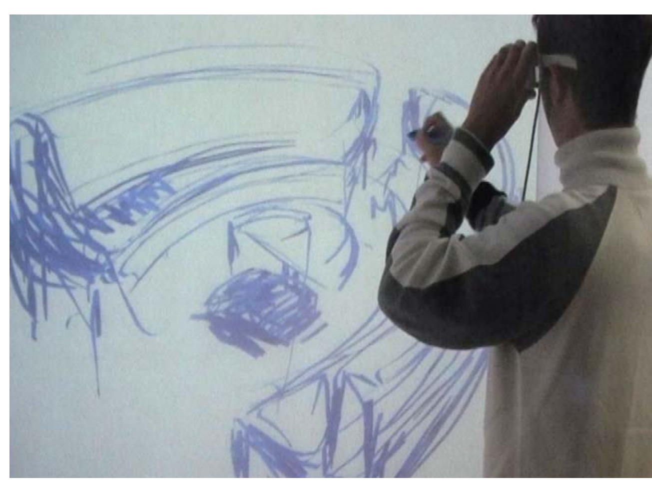

Fig. 5. Participant sketching a bar (3D).

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 (Fig. 6). In the hedonic quality identification (HQ-I), 3D is ranked significantly higher than 2D ($M_{3D} = 4.55$, $SD_{3D} = .84$; $M_{2D} = 3.70$, $SD_{2D} = 1.13$) $t = -3.33$, $p < .001$. This applies also to the hedonic quality simulation (HQ-S; $M_{3D} = 5.94$, $SD_{3D} = .58$; $M_{2D} = 5.14$, $SD_{2D} = 1.32$) $t = -3.14$,

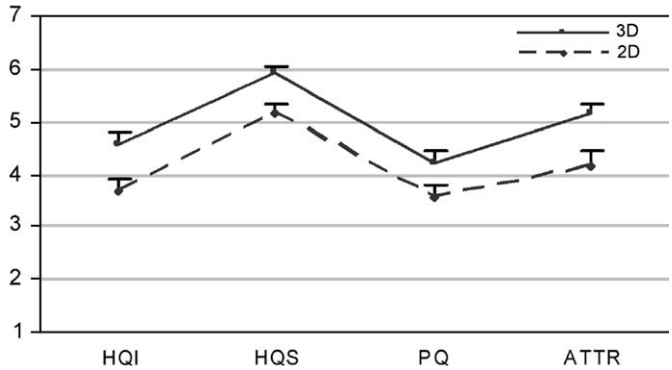

Fig. 6. Results of the AttrakDiff questionnaire for 2D and 3D sketching techniques.

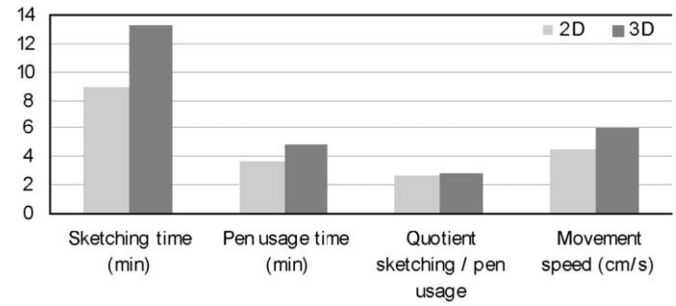

Fig. 7. Sketching and pen usage time, speed.

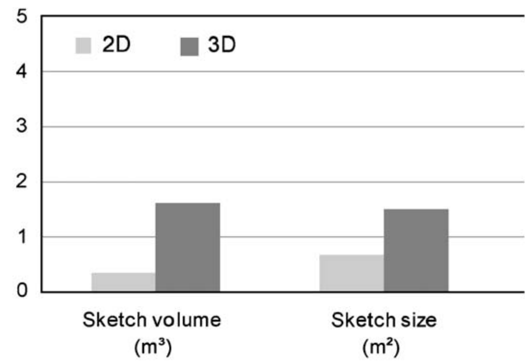

Fig. 8. Sketch volume and size.

$p<.001$, 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 attraction (ATT) of the 3D condition ($M_{3D}=5.16$, $SD_{3D}=.95$) was perceived to be significantly higher than that of the 2D condition ($M_{2D}=4.17$, $SD_{2D}=1.28$) $t=-3.94$, $p<.001$.

The answers to the follow-up questionnaire on a 5-level 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 3D than for 2D. Participants also answered that they could realize their ideas faster in the 3D than in the 2D condition ($median_{3D}=3.00$, $IQR_{3D}=2.25$–4.00; $median_{2D}=2.00$, $IQR_{2D}=1.00$–3.00; $Z=-2.790$, $p<.005$; based on the Wilcoxon test). The item on fluency of the sketching process almost reached statistical significance towards a higher value for 3D 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. The item that asked whether the sketching technique was physically exhausting received equally low ratings in both conditions ($median_{2D}=median_{3D}=2.0$; "disagree", which means marginally exhausting).

4.5.2. *Measured user behaviour*

Participants moved 33 percent faster in the 3D condition than in the 2D one ($M_{3D}=.061\,\mathrm{m/s}$, $SD_{3D}=.019$; $M_{2D}=.046\,\mathrm{m/s}$, $SD_{2D}=.031$) $t=-2.25$, $p<.035$ (Fig. 7). The average time taken for creating a 3D sketch was 50 percent longer than for a 2D one ($M_{3D}=13.38\,\mathrm{min}$, $SD_{3D}=5.54$; $M_{2D}=8.97\,\mathrm{min}$, $SD_{2D}=5.26$) $t=-3.88$, $p<.001$. The time in which participants used (pressed) the pen for creating sketches was 37 percent longer in the 3D than in the 2D condition ($M_{3D}=4.96\,\mathrm{min}$, $SD_{3D}=2.17$; $M_{2D}=3.64\,\mathrm{min}$, $SD_{2D}=2.56$) $t=-3.88$, $p<.001$. 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 from the very aesthetic to scribbles, which were hard to interpret. Examples are shown in Figs. 3–5 and 10. 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 3D condition and by three subjects in the 2D condition.

For each sketch we calculated the smallest enclosing box. We found the volume five times bigger for 3D sketches ($M_{3D}=1.64\,\mathrm{m}^3$, $SD_{3D}=1.65$; $M_{2D}=.34\,\mathrm{m}^3$, $SD_{2D}=.45$) $t=-4.20$, $p<.0001$ (Fig. 8). We also compared the sizes of the sketches' largest sides. Also in this comparison 3D sketches were twice as large as 2D ones ($M_{3D}=1.50\,\mathrm{m}^2$, $SD_{3D}=.98$; $M_{2D}=.67\,\mathrm{m}^2$, $SD_{2D}=.49$) $t=-4.83$, $p<.0001$.

The perspective character of the sketches was determined according to Urban [36]. Zero to two points could be assigned to each sketch depending on the number of objects that showed a perspective or isometric 3D attempt. If the whole sketch was drawn as a three-dimensional composition, six points were assigned. Note that if in the 3D condition sketches consisted only of "slices" in a row, and the slices showed no perspective character, no points were assigned. A perspective character according to this measure was much more apparent in the 3D than in the 2D condition ($M_{3D}=4.58$, $SD_{3D}=2.09$; $M_{2D}=2.08$, $SD_{2D}=2.46$) $t=-4.40$, $p<.0001$ (Fig. 9).

Finally, the exported VRML files contained twice as many points (details) for 3D sketches than for 2D sketches ($M_{3D}=4318$, $SD_{3D}=2628$; $M_{2D}=2399$, $SD_{2D}=1625$) $t=-3.15$, $p<.005$ (Fig. 9).

4.5.4. *Observed user's behaviour*

One important observation during our experiment was that eight out of the 24 participants incorporated 3D elements in their 2D sketches; four of them in task one, the other four in task two. In this context, the 3D elements were mostly surfaces and panes expanding into the z-dimension (Fig. 10). Most of the participants who noticed their "mistake" were very surprised and commented verbally, e.g. "I am always sliding into 3D" or "I can't think two-dimensionally any more". Especially in those cases where participants had to work in the 3D condition first, some participants needed extra time to concentrate on the 2D condition.

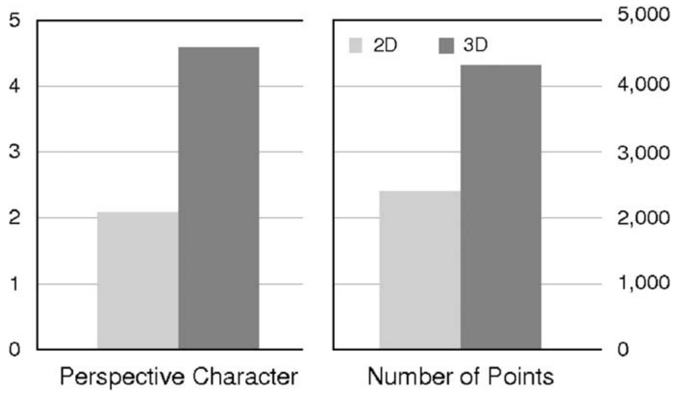

Fig. 9. Perspective character of the sketches and number of points (detail).

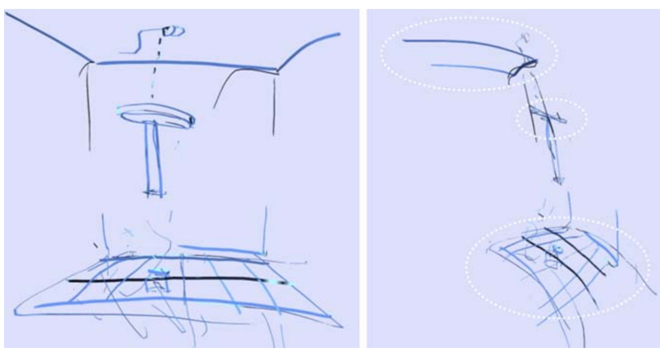

Fig. 10. Front and side view of a sketch of a hanging table in the 2D condition (task one). 3D elements are marked white in the side view.

Additionally, our observation revealed a very interactive behaviour for many subjects during the 3D sketching task. First of all, participants moved around and took different perspectives onto their sketches (this observation is supported by the significantly higher movement speed in the 3D condition, Fig. 7). Many used the walls of the Cave as endpoints for their designs. As all tasks were related to furniture design, participants sketched most of the design in relation to their body proportions. We regularly observed designers who tried to sit down in their sketches and who looked below sketched tables or walked around and looked at their sketch from different perspectives. Thus, because most of the participants were very agile while performing the sketching, sketching and moving can be regarded as inter-connected.

4.5.5. *Qualitative content analysis of user statements*

To obtain information about how 3D sketching and "quasi-2D" sketching differ in immersive virtual environments and to gain first hypotheses about how 3D immersion additionally supports sketching activities, we conducted a questionnaire that consisted of three open questions. The questionnaire was presented subsequent to the sketching tasks and corresponded to the sketching experience designers made during the workshop. Its major aim was to summarize the subjectively perceived advantages and disadvantages of both conditions and to report deficiencies of conventional 2D sketching on paper.

In the questionnaire, participants were first asked whether the specific sketching method had helped them to solve the design problem. Additionally, they were requested to name the reasons for their decision. Secondly, participants were asked about potential problems and obstacles during the sketching process, and about their key experiences made while working on the design-problems in the Cave. The questionnaire also asked about the additional use of paper and pencil in the virtual sketching process.

To analyze the answers given in the questionnaire and to quantify the collected data, we used a qualitative content analysis following Mayring [28]. Therefore, three independent coders first read through part of the material to develop an encoding scheme that could be applied to analyze all three questions in one step. In the second phase, the preliminary encoding scheme was tested on the whole material. We identified six main categories, each consisting of several subcategories. Each subcategory was also rated as positive or negative with regard to the corresponding sketching method.

Table 3 subsumes labelling and description of the main categories together with exemplary user statements and the overall positive and negative ratings named by the participants.

The qualitative content analysis validates the findings of the focus groups yielding the following results: we counted 59 negative statements under 2D condition and 53 negative statements under 3D condition in an immersive sketching environment. As positive statements we found 14 under 2D condition and 37 under 3D condition. Fig. 11 shows the total number of user statements distributed to our 6 subcategories.

Only one participant made paper sketches prior to sketching in three dimensions. When asked for an overall comparison of 3D sketching with conventional 2D paper-and-pencil sketching, only 1 participant preferred conventional 2D sketching, whereas 11 participants appreciated 3D sketching. 7 participants rated conventional 2D- and 3D-sketching equally.

According to our survey, the largest problem in virtual sketching concerns the sensorimotor control in 3D virtual environments. In this category we counted 37 negative statements under 2D condition and 33 negative statements under 3D condition, but no positive statements. In this context, participants basically complained about the difficulty to find connection points in space and criticized the deficient precision of the devices. Another problem that was often mentioned was the restricted ability to draw straight lines and to sketch at different depths in the 3D environment. In our opinion, these effects are not surprising given the users' lack of experience and expertise in working in 3D environments. Moreover, we found that sketching performance improved over time. Regarding this fact, it can be assumed that difficulties in sensorimotor control can be equalized with a suitable training programme and growing experience. Fig. 12 subsumes the distribution of user statements on the sensorimotor control of the sketching tools and the interaction with the environment.

There were also some difficulties with the *ergonomics* of the devices and the Cave construction. We found 6 negative statements under 2D and 5 negative statements under 3D condition, but only one positive statement. What participants criticized the most were the hybrid pencil, the missing haptic feedback and the size of the Cave. With regard to the pen, users mostly complained about the offset between the physical and virtual parts of the pen and also about the delay of up to 200 ms caused by the magnetic tracking equipment and the smoothing algorithm. Fig. 13 summarizes the corresponding user statements.

The *methodological support* of 3D immersive sketching was discussed controversially by the users with a sum of 3 negative statements and 9 positive statements under both 2D and 3D conditions. Fig. 14 shows the relevant results of the user survey. What was complimented the most was the opportunity to develop creative design ideas with the sketching tools, the possibility to interact with the sketch, to easily communicate design ideas to other participants, to externalize ideas and solution approaches and to experiment in parallel with various

Table 3
Categories derived from user statements and their total frequencies.

Category	Description	Example	Total frequencies	
			2D condition	3D condition
Sensorimotoric control of the sketching process	Selecting fixed points in the 3D-space; reaction time; delay; occlusion, precision, sketching of lines, sketching on different levels, sketching in depth, etc.	"I felt there was a gap between my hand and the virtual tool."	0 positive statements; 37 negative statements	0 positive statements; 33 negative statements
Ergonomics	Use of working devices, e.g. pencils, gloves; haptic feedback; Cave-design, etc.	"I missed the physical resistance, and the cables of the magnetic tracking sensor pulled my hand in the wrong direction."	1 positive statement; 6 negative statements	1 positive statement; 5 negative statements
Methodological Support	Creation of ideas; solution finding; communication tool; analysis; association, etc.	"The sketching technique supported me in keeping my ideas."	4 positive statements; 1 negative statement	5 positive statements; 2 negative statements
Functionalities	Missing functionalities, e.g. erasing, zooming, integration into CAD	"I would like to have a snapping function."	1 positive statement; 1 negative statement	0 positive statements; 2 negative statements
Comparison traditional paper sketching vs. *immersive 3D sketching*	Paper sketching vs. virtual sketching; CAD vs. sketching;	"I had a greater sense of freedom compared to paper sketching."	1 positive statement; 2 negative statements	0 positive statements; 1 negative statement
Sketching Process	Cognitive support (alertness, learnability, body inclusion); physical factors (feeling of directly working on the model); reflection (proportionateness, implementation, spatiality, spatial thinking, orientation, perception of height, interior view on the sketches); inspiration (imagination, experience, fun, curiosity), etc.	"The immersive sketching technique enabled me to slip into and through the graphics."	7 positive statements; 12 negative statements	31 positive statements; 10 negative statements

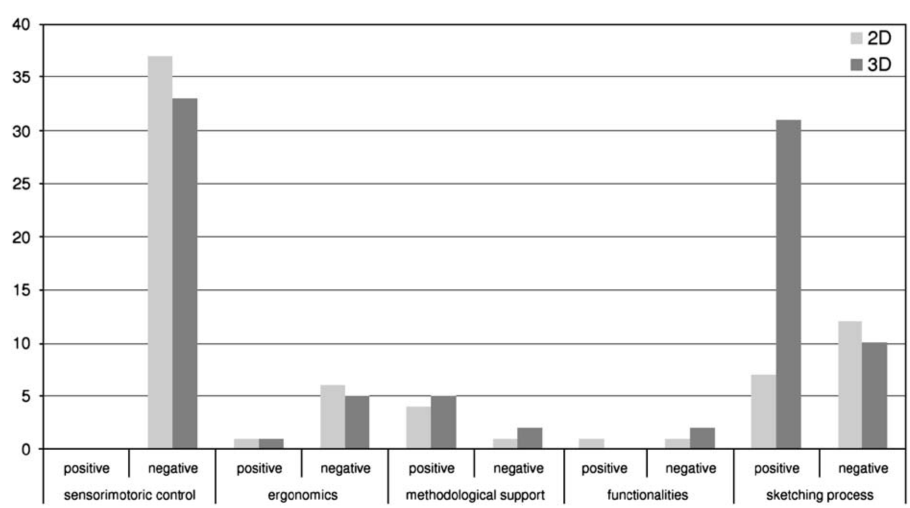

Fig. 11. Total number of user statements.

solutions. What was criticized the most was the deficient opportunity to implement ideas that had already been generated. There was also a call for wireless sketching tools and to additional *functionalities* in the virtual sketching process, e.g. erasing and snapping.

In the majority of cases, the *sketching process* itself was rated positive by the users. Fig. 15 subsumes the corresponding user statements. In sum, we counted 12 negative statements under 2D conditions and 10 under 3D conditions in comparison to 7 positive statements under 2D and 31 positive statements under 3D conditions. In this context, participants praised 3D immersive sketching for its ability to simplify spatial perception, to support cognition and reflection processes and to foster inspiration and creativity. As another prominent benefit, participants mentioned the opportunity to implement objects in their correct spatiality or accommodation. In this context, participants liked to go around the sketch and to observe the object from different perspectives. They also desired the spatial feedback directly given by the

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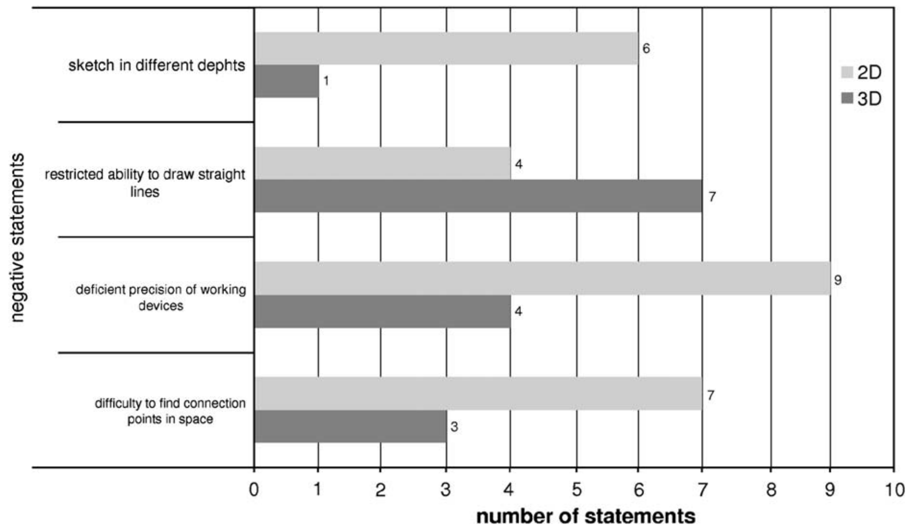

Fig. 12. User statements on sensorimotor control.

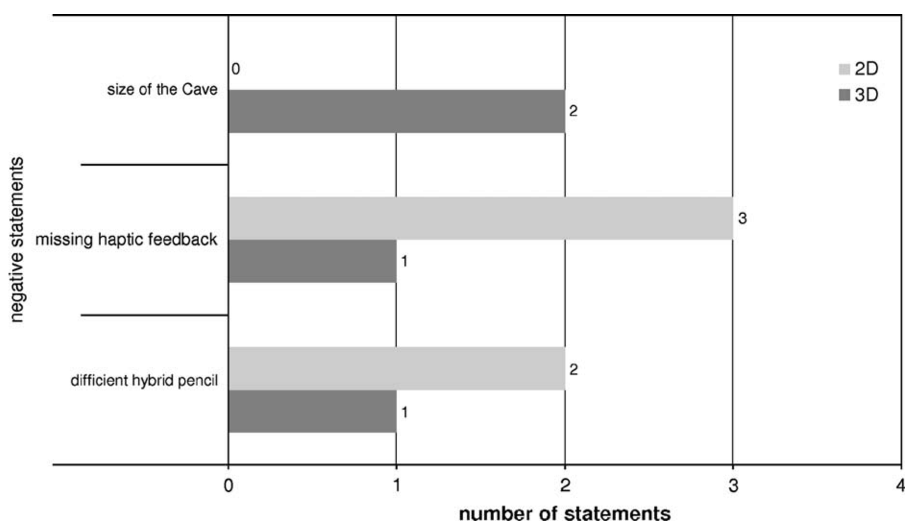

Fig. 13. User statements on ergonomics.

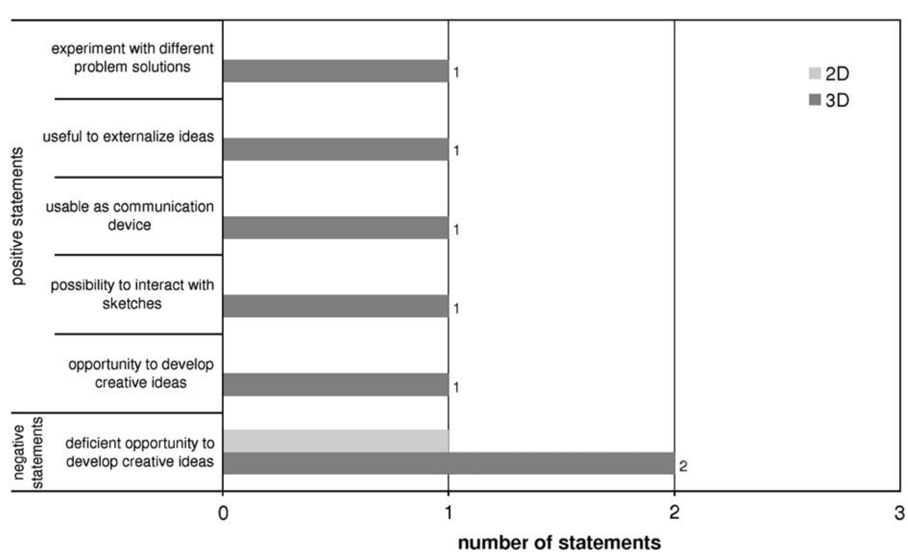

Fig. 14. User statements on methodological support.

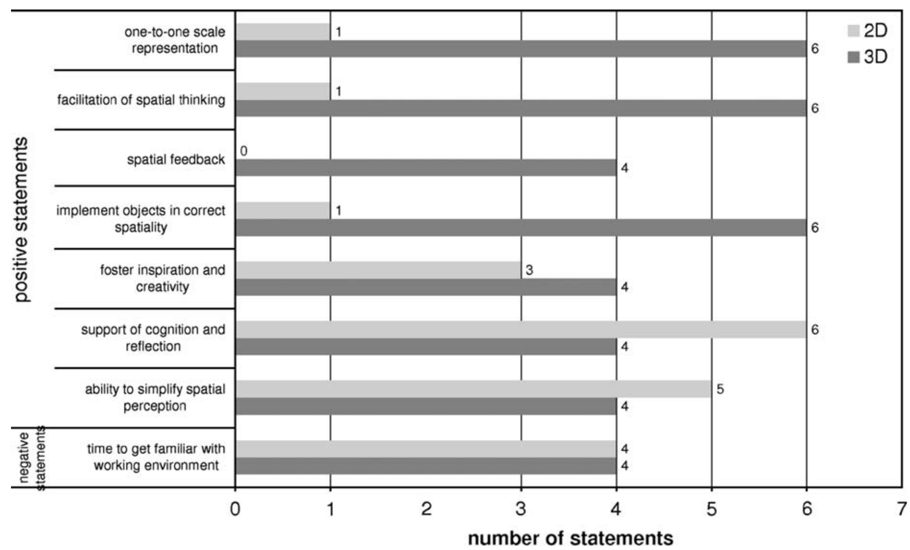

Fig. 15. User statements on the sketching process.

immersive 3D sketching system. Following the user statements, the Cave facilitates spatial thinking by supporting the development of three-dimensional problem representations and by giving the opportunity to represent objects in a one-to-one scale. The only issue that was criticized in this context was the time required to get familiar with the working environment, especially given the long working experience in conventional 2D sketching.

4.6. Discussion

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

However, we get a different picture if we weigh the opinions of the 24 study participants higher than the opinion of the one academic expert who rated the sketches. 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 3D sketching as a promising creative design method.

User ratings suggest that the sketching process differs regarding externalizing speed and fluency in favour of the 3D condition. In contrast, the quotient between measured overall sketching time and measured 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 might be an indicator that the self-communication process of externalizing and reflecting is a low-level process that is independent of the media (in contradiction to hypothesis 3). On the other hand, participants sketched significantly longer in the 3D condition. The behaviour of the participants in the 3D condition was more interactive, e.g. sitting down in sketched chairs and walking in virtual bars. Both results support hypothesis 3. A deeper analysis of the actual sketching process in terms of mental and sensorimotor sub-processes is needed in order to understand these changes in detail (cf. [38]).

Further support for our first hypothesis comes from the findings about using 3D elements also in the 2D condition and having more perspective elements in the 3D sketches. It is assumed that designers mentally represent, process and externalize (by moving their hands) mental sketches originally in three dimensions and that 3D 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, to some extent we called into question our initial decision to design the "quasi-2D" condition under the same technical conditions as the 3D condition. Some of the user statements favouring the 3D condition might reflect the artificially designed 2D condition, in which it took extra effort to remain on the plane, with no compensation reward.

Further studies could 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, "quasi-2D" and 3D 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 conventional 2D paper sketching with "sketching in the air" could also reveal differences in the elements used in the sketches, namely visual-graphical, schematic, symbolical, and verbal elements [37,39], for which we could find no differences in our study.

The results suggest that designers "accept" 3D sketching as a medium for expressing and developing design variants and solutions. Many of the participants were very enthusiastic about the new sketching possibilities. One 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 2D condition can hardly be compared with sketching on paper, we can say that under the same technical conditions, 3D sketching is the preferred interaction technique for sketching in space. The results from the AttrakDiff questionnaire support this claim. Not only did designers identify themselves more with 3D sketching than with the 2D condition, they also feel more stimulated by the former, which could be explained by the novelty of the technology. They also rated the pragmatic, solution-related quality higher for 3D sketching than for the 2D condition. This adds support for our hypotheses 1, 2, and 3.

A questionnaire was used to summarize the advantages and disadvantages of the 3D immersive sketching system from the user's perspective. The sensorimotor control functions (e.g. difficulty to find connection points, deficient precision of working devices, problems with drawing straight lines) emerged as one of the biggest problems. In our opinion, most of these problems might be equalized with adequate training and more experience with 3D systems. Evidence for this assumption comes from the observation that sketching performance increased over time during our experiment. Another problem concerned the ergonomics of the system. In this respect, participants mostly complained about a lack of haptic feedback and the relatively small Cave. With regard to methodological supporting functions, users on the one hand criticized the difficulty to implement generated ideas in the 3D system. On the other hand, they praised 3D sketching for its ability to simplify human spatial perception, to support human cognition and reflection processes and to foster inspiration and creativity. According to the results of our survey, the biggest advantage of 3D immersive sketching lies in the sketching process itself. In this context, we counted an almost equal number of negative statements under 2D and 3D conditions (12 for 2D, 10 for 3D), whereas the majority of positive statements were under 3D conditions (7 for 2D, 31 for 3D). In this respect, especially the system's ability to foster inspiration and to improve the recognition of spatiality and spatial thinking were underlined by participants under 3D conditions. That in turn emphasizes the importance of 3D sketching in comparison with regular 2D sketching techniques as a supporting method in early stages of product design.

5. Conclusion and outlook

Due to the interest we received from the design community and the results of our study we are optimistic that 3D 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 3D sketching and its novelty. Other aspects, e.g. formability of the sketch, could not be evaluated due to the underdeveloped functionality of our prototype. In order to increase usability, further research is needed among other things into reducing the tracking-induced time-lag, e.g. by means of Kalman filters, and into reducing the noise caused by the tracking system, which prevents the drawing of smooth lines and shapes.

From the literature (e.g. [20]), 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 3D sketching. Thus we have developed a tangible two-handed Bezier tool and a free-form extrusion tool that can be controlled entirely by direct physical manipulation and without issuing commands. They will be the subjects of further studies. As progress towards 3D sketching, new tools are needed that provide functionality that goes beyond straight one-to-one mappings of body movements to operations digital geometry. Such systems could allow 3D curve sketching on physical surfaces (e.g. [40]), retrieve parametrised 3D CAD geometries from freehand 3D sketches (e.g. [20]), support different levels of granularity (e.g. [41]) and integrate editing tasks. However, it is important that new sketching tools preserve the sketch character of the models (e.g. open or twisted lines), which is crucial to the associativity and ambiguousness of sketches, which in turn is essential to support creativity and solution finding in early conceptual phases.

The results for the focus groups, our user study and the qualitative content analysis of user statements could provide some evidence regarding the benefits of 3D sketching and its specific features in the design process. Nevertheless, in order to find fields of application and to legitimate the expensive equipment, more specific research should go into operational systems in real industrial environments that integrate into the virtual product creation process organizationally and technically.

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