EUROGRAPHICS Symposium on Sketch-Based Interfaces and Modeling (2010)
M. Alexa and E. Do (Editors)

Shape Modeling with Sketched Feature Lines in Immersive 3D Environments

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Abstract

In this paper we address the question whether automatic shape creation using sketched strokes as input in an immersive 3D environment supports the sketching process in early phases of product design. To investigate this question, model creation and deformation algorithms of the desktop sketch-based modeling tool FiberMesh [NISA07] were transferred to an immersive 3D environment. A comparative user study was conducted among twelve design students and professional designers. Line-based sketching in a 3D environment and sketch-based modeling, both in a 3D and 2D environment were compared. The analysis of the study yielded few differences between the conditions, but two findings were made: usability for a creative sketching task was perceived higher for line-based sketching than for sketch-based modeling - both in an immersive 3D environment. Shape modeling in immersive 3D environments was perceived as more stimulating and attractive than under 2D conditions.

Categories and Subject Descriptors (according to ACM CCS): I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction techniques, I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual reality

1. Introduction

Sketching is an important method in product development and engineering design, especially during the early design phases [Röm02,HSS98]. In this context, sketches serve as an externalization of mental concepts [Tve02]. Moreover, various authors describe sketching as a reflective process of self-communication, in which a designer draws a sketch, reflects on the drawn image and generates new ideas while working with the sketch [Tve02, HSS98, Bux07].

Sketch-based modeling is an attempt to preserve the established advantages of sketching within a digital modeling environment. The focus of many researchers in this context is put on intuitive modeling techniques that avoid extensive parameter input (cf. [IMT99, SPS01, Hum00, IH03, PL03, SWSJ05, KH06, KS07, BBS08]).

In the field of virtual product creation, immersive 3D environments are used in combination with tools for engineering design that support designers during the whole design process [KS08]. Special attention is paid to the early design phases as they are considered to have a major impact on quality and costs of a future product [HSS98].

Consequently, the aim of this paper is to combine sketch-based modeling with the visual perception and interaction provided by an immersive 3D environment to investigate whether this approach can support designers in early product design phases. Sketch-based model creation in an immersive 3D environment aims at enhancing self-communication during the sketching process. A 3D environment alters both, the externalization (i.e. the act of drawing) and the reflection (i.e. the visual perception of the sketch), in a profound way.

We make two significant contributions:

1. We extend a tool for the automatic creation of voluminous 3D objects based on sketched strokes [NISA07] for use in an immersive 3D environment. In contrast to other existing tools for modeling in immersive 3D environments [SPS01, PL03] this sketch-based modeling approach allows for direct and fast creation of objects. One may speculate that this increase in speed supports the sketching process, as quickness can be seen as an important property of sketching (cf. [Sac01,Bux07]). However, it might also limit the sketch-like appearance and thus the

DOI: 10.2312/SBM/SBM10/127-134

ambiguity of the model which is regarded as supportive to creative design processes (cf. [Bux07]).

2. Rather than informally assessing the performance of this new tool, we perform a controlled user study to evaluate sketching in immersive 3D environments. Despite various studies in this field, only little is known about the usability of interaction techniques for immersive sketching and modeling. Past studies targeted primarily domains like sensorimotor coordination of sketching movements [Hum00, IWM*09], haptic support [KAM*08] or feasibility of immersive sketching [DML04, Mül07, PL03]. In particular the question remains unanswered whether stroke-, surface- or object-based interaction techniques provide optimal support for creative design tasks. We set up two hypotheses which were investigated in a comparative user study:

Hypothesis 1: Immersive 3D media are better suited to externalize images of voluminous objects (e.g. inner images of products) than 2D media.

Hypothesis 2: The total workload of designing voluminous objects can be diminished by reducing the number of motoric process steps (e.g. movements) that are necessary to create these objects.

We first describe the extension of FiberMesh [NISA07] for immersive environments in section 2. The main challenge was to enhance a tool for 3D sketching and interaction which was originally developed for a 2D context. Then we describe a user study (section 3), investigating two hypotheses: hypothesis one is based on tests against the 2D version of FiberMesh and hypothesis two is based on tests against a tool for sketching lines in 3D. Preferences are recorded using two standardized analysis of variance (ANOVA) tests. We discuss the results of this analysis in section 4.

2. ImmersiveFiberMesh Application

In an attempt to provide a fast and immersive way to create and examine objects, an application was developed that offers immersive shape creation: the basic functionalities of object creation and deformation of FiberMesh [NISA07] were combined with the spatial visualization and interaction in an immersive 3D environment.

FiberMesh [NISA07] is a desktop system for freeform modeling, based on silhouette sketching that follows the same basic idea as Igarashi et al.'s Teddy [IMT99] but uses different algorithms. Its 'blobby inflation' [CA09] approach of sketch-based modeling offers a straightforward and fluent way to create virtual 3D objects. FiberMesh creates and interactively changes a 3D model from 2D input strokes. The user's strokes remain visible on the model and serve as handles to change the geometry of the model.

Almost all aspects of FiberMesh need to be reconsidered for 3D input: curves drawn in 3D are not necessarily planar and user interaction is not restricted to a plane. This has consequences for the creation and deformation of shapes. The system uses OpenSG as a scenegraph system. It recalculates the input from the 3D input devices and transfers the result to the FiberMesh algorithm. The response of FiberMesh is then transfered to OpenSG to be displayed in the immersive 3D environment. We first discuss the input modalities support in our system and then how we modify the creation and deformation algorithms to handle this input.

2.1. Tangible User Interface for ImmersiveFiberMesh

The tangible user interfaces (TUI) of the system are a pen and a gripper. In using a pen for the creation of lines and shapes, the pencil and paper metaphor is applied. The pen is held in the way of a fountain pen to use fine motor skills. The embodiment of the gripper-TUI makes use of the everyday experience that grippers are used to bend objects. So the gripper is held like the gripper of a handyman and gross motor skills are used to deform objects (cf. [IWM*09]).

Drawing into a projected virtual scene with a real pen poses perceptual problems, e.g. the accommodation-vergence conflict [DM96]: the real pen is at another physical location than the projected stroke, which lives on the projection screens. Even in stereoscopic display, the human visual system still focuses onto the screen walls, leading to the pen being out of focus. To attenuate this problem we display an image of the pen in the virtual scene – this pen is also displayed on the screens, so that the human visual system can accommodate on the screens and perceive pen and stroke focused.

2.2. Creation of shapes

The user interacts with the system by first drawing an input stroke with the pen. The original FiberMesh algorithm is based on a closed planar curve that serves as a silhouette of a symmetrically inflated rotund shape (cf. [NISA07]). But a stroke in 3D is not necessarily planar. The additional 3D information could be exploited: the shape is designed to minimize a smoothness functional while embedding the input stroke. Thus, a 3D curve could be used to control the initial shape not only along a silhouette but also in depth.

However, we have found out that users have difficulties controlling all three dimensions of their strokes. In fact, it is already difficult to draw a closed curve, i.e. guiding the pen to the 3D position where the initial curve started. Consequently, we limit the curve to 2D by fitting an invisible auxiliary plane through the stroke. Then, the stroke is projected onto the plane, it is closed, and the curve is taken to be planar and handled as in the original approach. Figure 1 shows this procedure.

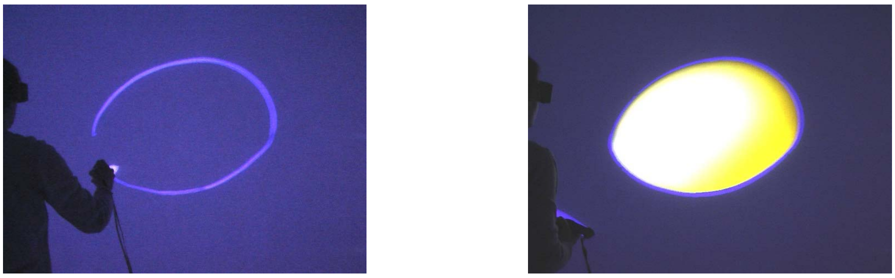

Figure 1: *Input stroke and created virtual 3D object*

2.3. Deformation of shapes

Shapes can be deformed by using the gripper to pull any *handle* on the shape. Handles are either strokes that have been drawn by the user to create a shape or any other line specifically drawn for the purpose of serving as a deformation handle. A handle can be added by drawing an open stroke near an object starting and ending outside the input silhouette (figure 3). The stroke is then orthogonal projected onto the auxiliary plane of the initial input stroke and handled as in the original approach: it is projected onto the mesh and duplicated to the backside of the object. The drawing *onto* a virtual 3D object, i.e. tracing its surface with a stroke, turned out to be difficult. A solution was found in just drawing *near* an object, i.e. the stroke can be outside the object within a threshold value or cross the object.

The deformation is based on 3D coordinates: The user provides constraints for the deformation by pulling a vertex of a handle-stroke in any direction, using the gripper. The deformation algorithm consists of two main steps: curve deformation and surface optimization. During pulling, these operations are solved sequentially to gain an interactive update of the mesh. The user deforms a curve by pulling a deformation handle. A region of interest is calculated and a smoothness functional is minimized to deform the handle-stroke. The new stroke positions are used as an input for surface optimization, taking stroke positions as positional constraints (cf. [NISA07]). Figures 2 - 4 illustrate the interaction.

2.4. Limitations

The approach handles interaction without parameter input at the expense of level of detail. The user's influence on the initial creation of the object is limited to the specification of its silhouette. The rotund shape and depth of the resulting object is set by the system. To change depth and shape of an object, deformation functionality can be used. Still, the ImmersiveFiberMesh system in its present state is limited to the category of rotund objects.

While the FiberMesh application uses one single mesh and hence one object that can be extruded and deformed, ImmersiveFiberMesh provides the opportunity to use the whole space of the immersive environment by creating multiple objects. Limiting the sketching process to only one object would mean to unnecessarily restrict the design process as well as the use of the application. Each object is a mesh of its own. Since extrusion of the mesh is not featured, deformation of one object does not propagate to connected objects.

3. User Study

A comparative study was set up, with the general aim of understanding how sketching in immersive 3D media is applicable for the creation of early prototypes. In particular, the study investigated the influence of the dimensionality of interaction space (i.e. immersive 3D media vs. 2D media) and interaction technique (i.e. sketch-based modeling vs. line-based sketching) on the sketching process.

We compared two different ways of sketch-based modeling in a CAVE to sketch-based object creation on a tablet PC. The two immersive approaches differed in terms of object creation, in an attempt to understand whether automatic object creation is perceived as helpful. In the following the conditions are described in detail.

Twelve design students and professional designers were invited. They were asked to accomplish two tasks under three sketching conditions. The study was conducted in the virtual reality laboratory of the Fraunhofer-Institute for Production Systems and Design Technology (IPK), Berlin.

3.1. Evaluated conditions

Three conditions were evaluated:

F2 – FiberMesh: 2D input sketch-based modeling that generates a 3D model from a 2D input stroke, as described in [NISA07].

F3 – ImmersiveFiberMesh: Immersive 3D sketch-based modeling that generates a 3D model from a 3D input stroke, as described in section 2.

S3 – SketchApp: Immersive 3D line-based sketching that displays strokes without additional model generation, as described in [IWM*09]. SketchApp provides drawing of

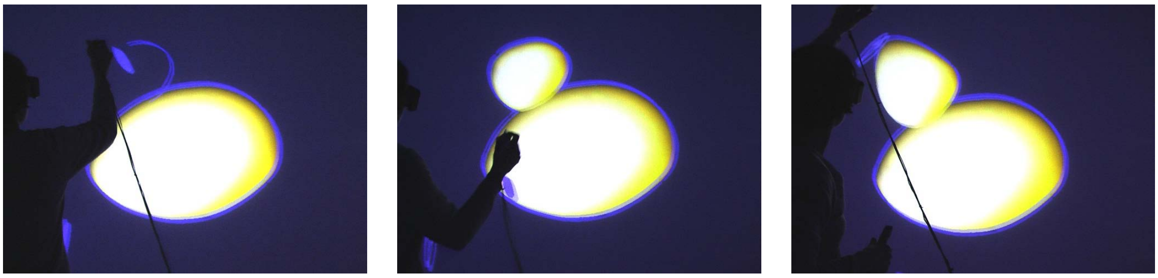

Figure 2: *Second input stroke and object, deformation of second object*

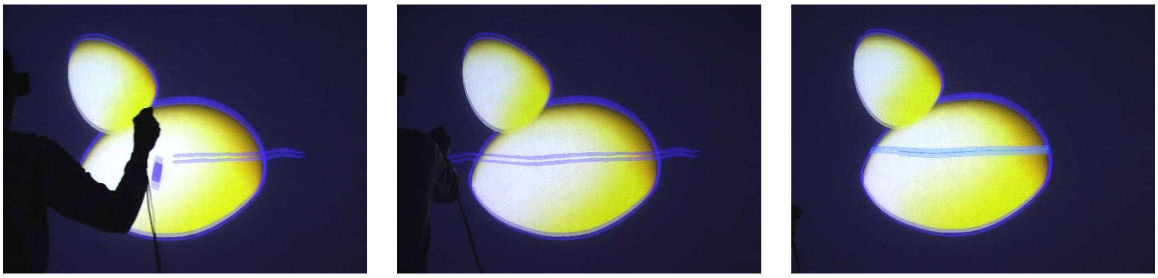

Figure 3: *Adding a stroke that is automatically wrapped around the object*

lines in an immersive 3D environment with a pressure-sensitive pen. Strokes are generated using strings of quads, altering stroke width according to the pressure on the pen.

Conditions F3 and S3 were run in a CAVE with five rear-projected walls (2.5-meter edge length). The system uses active stereo LCD shutter glasses (CrystalEyes) and magnetic tracking (Ascension MotionStar). Condition F2 was run on a tablet-PC (Lenovo ThinkPad), using a touchpen for interaction.

In order to investigate the influence of the space of interaction, ImmersiveFiberMesh and FiberMesh were compared. These two conditions differ with regard to the space of interaction (i.e. immersive 3D media vs. 2D media). The interaction techniques of the two conditions are different on a physical level, but have the same conception of automatic shape creation from simple input strokes. The consistency of interaction technique is limited by differences in input strategy (see further below). To investigate the influence of interaction technique, ImmersiveFiberMesh and SketchApp were compared. These two conditions have the same space of interaction (i.e. an immersive 3D environment), while the interaction techniques differ (i.e. sketch-based modeling vs. line-based sketching). FiberMesh and SketchApp differ in terms of both interaction technique and space of interaction and were not compared to each other.

The different strategies to extend objects in FiberMesh and ImmersiveFiberMesh limit the constancy of the interaction technique. The concept of FiberMesh is to create one model that can be extruded. To create an extrusion the user draws a closed stroke onto the model, rotates the model and draws the silhouette of the extrusion. ImmersiveFiberMesh provides no extrusion functionality. To extend an object the user creates another object at the appropriate location. Furthermore, in ImmersiveFiberMesh parts of the scene can be moved. Since FiberMesh does not allow to move parts of the model this also limits the comparability of the interaction techniques.

With these reservations, the interaction techniques of both conditions can be regarded as analogous: Both conditions use analogous methods to achieve the basic functionality of initial object creation and object-deformation. Other features of FiberMesh were not used during the study.

3.2. Method of collecting data

Two validated questionnaires were used. The NASA-TLX (NASA Task Load Index) [NAS88] assesses the subjective workload of a human-machine system in six subscales: *mental demand* - required mental and perceptual activity; *physical demand* - required physical activity; *temporal demand* - perceived time pressure; *effort* - how hard is it to accomplish the own level of performance; *own performance* - satisfaction with the own performance and *frustration* - insecurity, annoyance, stress etc. felt by the user.

In order to measure the user-perceived usability of the evaluated conditions the questionnaire AttrakDiff [Has04] was used. This questionnaire goes beyond standard usability

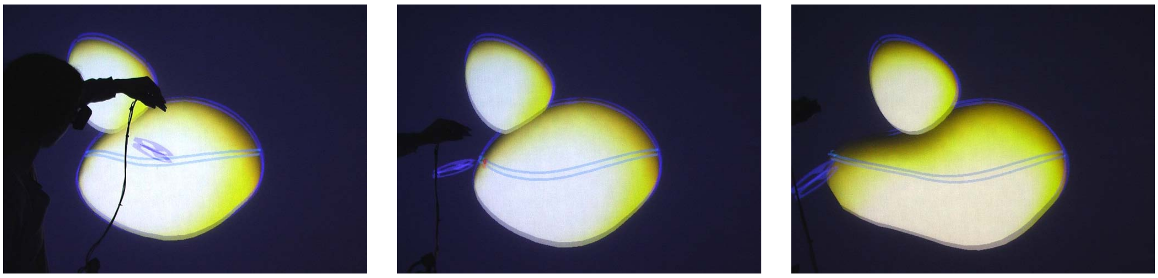

Figure 4: *Deforming a virtual 3D object by moving an added stroke*

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 (ATTR). Stimulation is related to the human need to develop personality and gaining new skills and knowledge. Identification stands for the user's 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 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 [Has04].

Additionally, a 5-point scale questionnaire with two items was employed:

Sketching process: The tool supported me well in expressing my idea of the object.

Completed sketch: The completed sketch was in accordance with my idea of the object.

Sketching process and *completed sketch* are two distinct qualities of a sketch that are both relevant in judging the suitability of a sketching condition.

3.3. Participants

Twelve test persons were invited, eleven male and one female, aging from 22 to 43 years, average age was 29.5 years ($SD = 6.4$). Eight persons were students of product or communication design, four were professional product designers. The students had a mean duration of study of 2.75 years ($SD = 1.28$), the mean professional experience of the product-designers was 7.25 years ($SD = 3.3$). All stated that they regularly sketch on paper and via computer and regularly use 3D CAD programs. Four had worked in virtual reality environments before, the others had no VR experience.

3.4. Tasks

Under each condition participants had to accomplish two tasks.

Task 1 - Sketching an object from memory: The purpose of the task was to let participants externalize a ***pre-existing inner image***. A round-shaped stool was shown to the participants. They were allowed to look at it and take it into their hands. Then the stool was taken away. The participants were asked to sketch the stool. Looking at the object, they were supposed to form an inner image. This mentally stored imagination of the object could be retrieved while sketching. Without the need to develop creative design ideas, the task was intended to address the adequacy of a condition with respect to externalizing an inner image of an object.

Task 2 - Designing an object: This task intended to address the level of support in a creative sketching process. Participants were asked to design a comfortable armchair. Because no visual pattern was given, they were supposed to develop their own imagination of an object.

The objects were chosen from the category of rotund objects because FiberMesh and the developed ImmersiveFiberMesh provide only the creation of this kind of objects. This restriction is inherent to the approach used. ImmersiveFiberMesh has no cutting functionality, and consequently cutting was also not to be used in FiberMesh, the task to create an angular shape could not be accomplished.

Figure 5 shows results designed by participants of the user study using ImmersiveFiberMesh.

3.5. Procedure of the study

The test persons could practice under each condition for 5 to 10 minutes. 10 minutes were provided to complete a task. The participants were then asked to answer the AttrakDiff questionnaire followed by the NASA-TLX questionnaire as well as the two additional questions. Then the second task was conducted in the same manner. The duration of the whole test per person was about two hours. Sketching conditions were permuted.

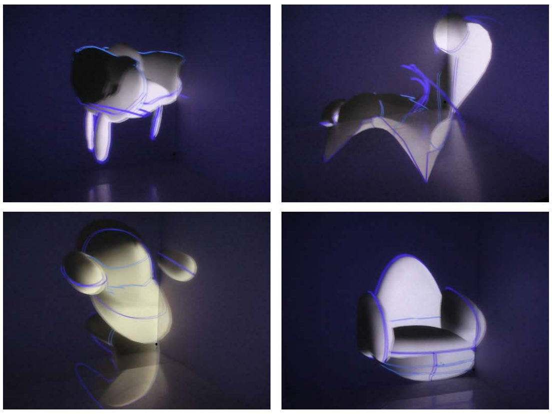

Figure 5: *Armchairs designed by participants for task 2, using ImmersiveFiberMesh*

3.6. Results

For the two questionnaires AttrakDiff and NASA-TLX a one-way ANOVA was conducted with the conditions FiberMesh, ImmersiveFiberMesh and SketchApp as three levels of the factor. The investigated dependent variables were the four dimensions of AttrakDiff (*pragmatic quality* (PQ), *hedonic quality identity* (HQ-I), *hedonic quality stimulation* (HQ-S) and *attraction* (ATTR) and the six dimensions of NASA-TLX (*mental demand, physical demand, temporal demand, own performance, effort* and *frustration*) as well as the mean value of the six dimensions of NASA-TLX (*subjective work load*). Only two comparisons were of interest (ImmersiveFiberMesh vs. FiberMesh and ImmersiveFiberMesh vs. SketchApp). A Scheffé post-hoc-test was conducted to investigate which pair of conditions reached a significant level. For the ordinal scaled two additional questions a Friedman test was conducted. Only those effects that reached statistical significance are reported.

AttrakDiff Regarding the *hedonic quality stimulation* (HQ-S) of task 1, ImmersiveFiberMesh ranked significantly higher than FiberMesh ($F(2,33) = 6.22; p < 0.05$).
ImmersiveFiberMesh: $M_{F3} = 2.02, SD_{F3} = 0.78$
FiberMesh: $M_{F2} = 1.17, SD_{F2} = 0.89$

For the *attraction* (ATTR) for task 2, ImmersiveFiberMesh ranked significantly higher than FiberMesh ($F(2,33) = 8.95; p < 0.05$).
ImmersiveFiberMesh: $M_{F3} = 1.21, SD_{F3} = 1.06$
FiberMesh: $M_{F2} = 0.21, SD_{F2} = 1.05$

Regarding the *pragmatic quality* (PQ) for task 2, SketchApp ranked significantly higher than ImmersiveFiberMesh ($F(2,33) = 8,56; p < 0.01$).
SketchApp: $M_{S3} = 0.95, SD_{S3} = 0.96$
ImmersiveFiberMesh: $M_{F3} = -0.30, SD_{F3} = 1.36$

Figure 6 and 7 show the mean values for task 1 and task 2.

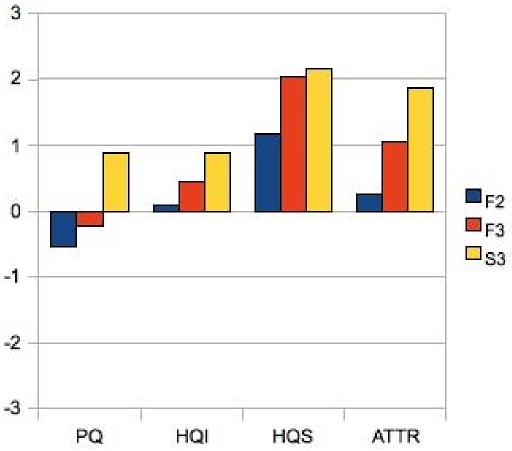

Figure 6: *AttrakDiff: Mean values for task 1*

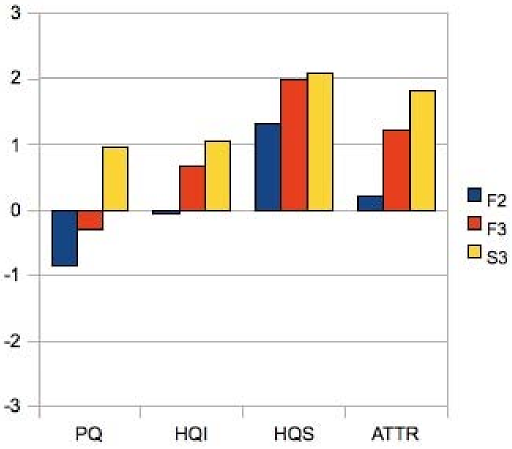

Figure 7: *AttrakDiff: Mean values for task 2*

NASA-TLX For the *physical demand* for task 1, ImmersiveFiberMesh was ranked significantly higher (i.e. more demanding) than FiberMesh ($F(2,33) = 4.96; p < 0.05$).
ImmersiveFiberMesh: $M_{F3} = 5.54, SD_{F3} = 2.57$
FiberMesh: $M_{F2} = 2.30, SD_{F2} = 2.89$

Regarding the dimension *own performance* for task 2, the comparison of ImmersiveFiberMesh and SketchApp almost reached a significant level (Scheffé post-hoc-test reached a significance of $p_{F3-S3} = 0.058$ between these two conditions). ImmersiveFiberMesh ($M_{F3} = 5.78, SD_{F3} = 2.65$) was ranked higher (i.e. poorer own performance) than SketchApp ($M_{S3} = 3.31, SD_{S3} = 2.38$).

Figure 8 and 9 show the mean values for task 1 and task 2.

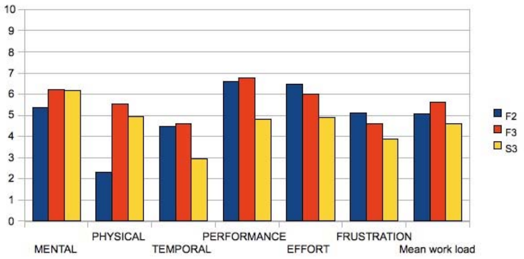

Figure 8: *NASA TLX: Mean values for task 1*

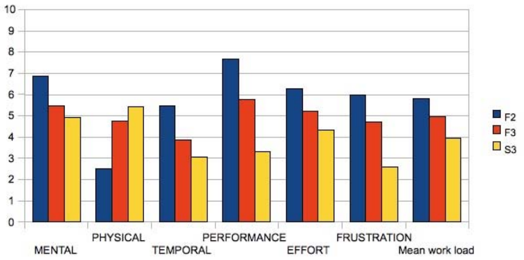

Figure 9: *NASA TLX: Mean values for task 2*

Additional questions The Friedman test for task 2 (designing an object), question 1 (concerning the sketching process) reached a significant level ($^{2}(2) = 13,29; p < 0.05$) and the additional pairwise Friedman test showed that the order of ranks between SketchApp and ImmersiveFiberMesh were significantly different ($^{2}_{F3-S3}(1) = 7.36; p < 0.05$). SketchApp was ranked higher (more supportive) than ImmersiveFiberMesh.
SketchApp: $median_{S3} = 3.00, IQR_{S3} = 3.25 - 4.00$; ImmersiveFiberMesh: $median_{F3} = 3.00, IQR_{F3} = 2.00 - 3.00$; FiberMesh: $median_{F2} = 2.00, IQR_{F2} = 1.25 - 2.75$.

4. Discussion & Conclusions

The analysis of the results of the study yielded few differences between the conditions, but some relevant findings were made.

Hypothesis 1 regarded 3D media and 2D media with respect to their suitability to externalize inner images of voluminous objects. Performing task 1, participants regarded ImmersiveFiberMesh as more stimulating than FiberMesh, even though at the same time, ImmersiveFiberMesh was perceived as more physically demanding. Task 1 was supposed to address the adequacy of a condition in externalizing an inner image of an object, in contrast to the creative development of an object without an external representation. As the HQ-S dimension describes the perceived novelty, stimulation and challenge of an interactive application, the result could indicate a stimulating impact of the immersive 3D environment while externalizing inner images.

Also, the *attraction* (ATTR) of ImmersiveFiberMesh with regard to the creative task (task 2, designing an armchair) was rated higher than that of FiberMesh. This task was designed to investigate to what extent conditions support creative sketching processes.

The results could be regarded as supportive to hypothesis 1 in the sense that the immersive 3D medium seemed to have a stimulating effect and the 3D condition was perceived as more attractive than the 2D condition for the creative sketching process. But with regard to the *pragmatic quality*, indicating the perceived usability of an application, no differences were found and the additional questions did not show any preferences.

Hypothesis 2 regarded SketchApp and ImmersiveFiberMesh with respect to the subjective workload. No results were found that support this hypothesis. The presumption that the total workload declines if the *system* creates an object from an input stroke instead of the *user* drawing the whole object could not be supported since no significant effects were found in the dimensions of the NASA-TLX among these two conditions.

Another result is that, with regard to the *pragmatic quality*, participants preferred SketchApp over ImmersiveFiberMesh to perform a design task (task 2, designing an armchair). The almost significant result for the dimension *own performance* (NASA TLX) of task 2 between these two conditions is in accordance with this result, assuming that the satisfaction with the own performance can be seen as related to the *pragmatic quality*. The additional questions also showed a preference of SketchApp over ImmersiveFiberMesh concerning the sketching process for task 2. These results seem to underline the importance of line-based sketching with regard to a creative design task.

Generally it has to be taken into account that functionality of the conditions differed (see section 3.1: 'Evaluated Conditions') and that the robustness of the applications applied for the conditions was also different. SketchApp was the most stable of the three applications and the FiberMesh version on the tablet PC was most unstable. Also, the adding of a stroke as deformation handle in ImmersiveFiberMesh sometimes failed and under certain conditions (e.g. intensive one-sided expansion) the model in both FiberMesh and ImmersiveFiberMesh expanded heavily on the opposed side of a pulled vertex. In certain cases the model even 'exploded'. This lack of robustness and predictability was criticized by participants of the study. Furthermore, ImmersiveFiberMesh featured no cutting tool which limited the creation of objects to rotund shapes. This restriction was also set for FiberMesh to keep the interaction technique comparable. SketchApp on the other hand does not limit sketching to a specific kind of objects.

Since these differences between the conditions narrow comparability, and also for the reason that the number of participants was small, this study can only give a tendency for further, formalized studies. Since users preferred line-based sketching in an immersive 3D environment over the provided sketch-based modeling in the same environment, a next step could be to investigate whether the *combination* of both, line-based sketching and sketch-based object-creation in a 3D environment, is an important feature to create a benefit for the early sketching process in 3D environments.

5. Acknowledgement

This work has been partially funded by the BMBF project AVILUSplus (01IM08002).

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