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Investigating the Learnability of Immersive Free-Hand Sketching

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Abstract

*Immersive modeling systems which allow for sketching and constructing three-dimensional product models receive growing interest from both academic research and industry [DBWB*00; FASM02; IWMS09; KAMD*08; KAML*01]. The potential of such systems is estimated in the possibility to create models in a one-to-one scale, to interact with product models and to reduce breaks between analogue and digital media during the development process [DBWB*00; IWMS09]. Despite the growing interest in 3D-sketching techniques, little is known so far about the ability of designers to create free-hand drawings in three-dimensional space. In particular, only few studies have investigated cognitive and sensorimotor processes during immersive sketching yet.*

This paper contributes to the research on immersive sketching by investigating the learnability of free-hand sketching in an experimental setting. In a study among 25 students, participants repeatedly sketched primitive shapes (circles, squares, balls, and cubes). Sketching performance was operationalized by the time needed to complete a sketch, the quality of the sketch, and the subjective mental workload of the designers. Results suggest a significant enhancement of sketching quality over time, but no change in the time needed to complete a sketch.

Categories and Subject Descriptors (according to ACM CCS): H.5.2 [User Interfaces]: Input devices and strategies; I.3.6 [Computer Graphics]: Methodology and Techniques – interaction techniques.

1. Introduction

From a psychological point of view, the development of technical products is based on complex information processing and the application of problem-solving strategies. Unfortunately, these complex requirements on human problem-solving abilities are confronted with the designer's cognitive and creative limitations resulting from a restricted working-memory capacity. To overcome these limitations and to foster a creative and innovative product development, suitable supporting systems are needed. Their development should be based on a profound understanding of the cognitive actions and perceptual processes that are involved in design problem-solving. One of the most challenging questions in this context is how external representations should be configured and how interaction with these representations should be implemented to efficiently combine mental and motor actions in a sensorimotor way.

This leads to the question whether virtual reality techniques are helpful for design problem-solving by providing information-rich, interactive visualizations in a 3D manner. More precisely, it is questioned whether virtual reality could be particularly helpful for assisting form defining processes like 3D-sketching. For this purpose, this paper investigates the support potential of 3D-sketching for design problem-solving in an experimental setting. The suitability of 3D-sketching for form defining processes is operationalized via the learnability of its application.

Various studies have shown that "sketching in the air" raises additional motor coordination efforts and that the resulting sketches show less details and precision than their analogue counterparts [DBWB*00; MI04; MRT02]. Keefe et al. [KAMD*08] investigated 3D-sketching techniques with and without haptic support. They found that undirected haptic support (artificial friction by means of force-feedback devices) provides only marginal aids compared to unsupported free-hand sketching. Other sketching techniques which provide additional visual feedback and allow for reversing actions lead to more detailed and precise sketches [KAMD*08].

Investigating the usability of immersive three-dimensional sketching and estimating its advantages is a difficult task. In particular, comparing immersive 3D-sketching to common 2D paper and pencil sketching techniques induces certain methodological challenges: as sketching on paper is a highly trained sensorimotor skill among industrial designers and artists, it can hardly be compared with the mostly unfamiliar technique of immersive sketching. Additionally, comparing immersive 3D- and traditional 2D- sketching would not only vary the dimensionality of the sketching-media but also other technical variables and perceptual parameters, e.g. kind of feedback, size of sketch or ergonomics of the sketching

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tool, resolution of the visualization system, lag and bandwidth of the tracking system and the accommodation-vergence conflict between user/pen and virtual sketch [DM96; MW93; MC99]. In consequence, the experimental design is confounded by several non-controlled influencing variables. This in turn makes it impossible for the experimenter to exactly determine the influencing variables in isolation. This conflict can be resolved in two different ways. First, an experimental set-up could be realized which systematically controls possible confounding variables, like resolution, screen size or kind of feedback. In this way, it could be determined which factors cause the majority of declared variance. Second, it is possible to use a non-comparative paradigm to measure the learnability of 3D-sketching. For this purpose, several data on 3D-sketching skills are collected at different measuring points, which are systematically distributed over time. It is hypothesized that the ability to sketch in a 3D-medium increases significantly over time.

The current experiment examines the learnability of pen-based immersive sketching technologies by means of basic sketching tasks. It was embedded in a larger examination which investigated the potential of a combined VR- and CAD-supported product development cycle, consisting of 3D-sketching, CAD-refinement, rapid prototyping and VR-based design review. Procedure and design of the overall study are referred in [WIZP*09].

Prior analyses revealed significant advantages of immersive sketching environments over common 2D-sketching techniques in terms of hedonic qualities (e.g. stimulation of the user) and interactive behaviour while sketching [IWMS09]. Additionally, empirical evidence was found for the potential of immersive 3D-sketching within an integrated product development process [WIZP*09]. In this context, most participants experienced a subjective progress of their sketching abilities during test trials. In order to validate this subjective impression, the learnability of immersive sketching techniques is systematically investigated in the current experiment. It raises the question of how easily immersive sketching skills can be acquired and improved by the users during a short test time interval. Therefore, an experimental design was realized which allowed for measuring learning curves of sketching primitive objects in three-dimensional space.

2. Method

2.1 Apparatus

The study was conducted in a laboratory setting: sketching was performed in the Virtual Reality (VR) Lab at Fraunhofer IPK Berlin. The experiment was set up in an immersive VR environment (Cave) with five back projected walls of 2.5m edge length each, employing a magnetic tracking system and active stereo vision. As sketching tool, a pen for drawing free-hand lines was provided which allowed for generating 3D-geometries directly in the virtual environment. A video-camera was used to record sketching activities. Interviews and questionnaire surveys were answered in a meeting room next to the laboratory.

2.2 Participants

The study was conducted among 25 students (14 male, 11 female, mean age 27.040, SD=7.074) partially from the Berlin University of the Arts (14 students) and partially from the Muthesius Academy of Fine Arts and Design Kiel (11 students). Their major subjects were industrial-, product- or communication design (12), architecture (4), visual arts (1) and visual arts for high school teaching (4).

69.2% of the students create paper-and-pencil sketches every week, 26.9% among them every day. 30.8% employ 3D-CAD software several times a week, 23.1% make use of it at least one time a week. 2D-CAD software was used less frequently: 3.8% use it every day, 23.1% employ it several times a week. 69.2% of the students had no experience with 3D-sketching in virtual environments, whereas 7.7% use it rather seldomly.

2.3 Materials

Participants were provided with a hybrid pen for drawing free-hand lines. This instrument allowed for generating 3D-geometries directly in the virtual environment [IWMS09]. For each sketched object a VRML-file of the sketched geometry and a log file were generated. The log file was processed by a program script in order to calculate behavioural parameters of the user (speed, sketching time, and viewing time).

To investigate the potential of 3D-sketching for form defining design processes, two different questionnaires were used in this study. One collected personal data and information about the individual sketching experience and had to be filled in prior to the experiment. The second questionnaire concerned the subjective workload imposed by the sketching tasks and had to be filled in after each task-cycle. For evaluating the quality of the produced sketches, a category system and an algorithm were developed as described in section 4.

3. Design and Procedure

3.1 Design

In general, to investigate the learnability of a certain skill, it is necessary to acquire performance data at different testing points and to compare them with regard to the degree of expertise achieved by the participants during several intermediate training sessions. Consequently, to test the learnability of 3D-sketching, performance measures of the participants' sketching abilities had to be collected several times during the experiment. Therefore, testing time was chosen as independent variable and was varied on three different levels: performance measures were collected after 0 minutes (test trial 1), 10 minutes (test trial 2) and 30 minutes (test trial 3) of experience with the 3D-sketching system. Thereby, performance measures at test trial 1 represent the participants' initial ability in 3D-sketching. For this study a rough resolution of only three testing points was considered sufficient because the intention was to test whether learning effects occur during a short time interval but not to evaluate the exact progression of the learning curve.

3.2 Procedure

In order to measure sketching abilities in three-dimensional space, participants had to draw four primitive shapes in the following order: circles and squares as flat shapes, followed by balls and cubes as volumetric shapes. All objects had to be drawn in a distance of 30 cm from the participants. Circles and balls had to be realized with radii of 30 cm; squares and cubes had to be drawn with an edge length of 30 cm each. Participants had to follow this procedure on each test trial during the experiment. No further specification was given to them of how to structure the sketching process. In addition, no time-limit was being set. Immediately after the test, participants had to fill out a questionnaire regarding the experienced general difficulty and mental workload imposed by the task.

In total, each participant was given a timeslot of 30 minutes of training experience plus the time needed to complete the test trials. In order to determine pre-existing skills in 3D-sketching, the experiment started with an initial test session (test trial 1; 0 minutes of experience with sketching system), followed by a training session of 10 minutes during which participants could become familiar with the sketching system. Afterwards, they had to perform test trial 2 followed by a training session of 20 minutes where participants should work on a specific sketching task (i.e. sketching a ceiling lamp, c.f. [WIZP*09]). The experiment ended after participants had finished test trial 3.

4. Measuring sketching performance

4.1 Time to complete the sketch

For measuring the time to complete a sketch, the sketching system provided an automatic mechanism which recorded start and end time for each individual drawing stroke into a log file. A script program was then used to accumulate the single stroke-times into a global variable which represented the time it actually took a participant to draw an object.

4.2 Quality of sketches

Quality of sketches was evaluated in two different ways. First, it was measured qualitatively by applying a category system which was specifically developed for this purpose. Within this scoring system, parameters like “line straightness” or “matching of two lines” were rated on three-point scales. Single scorings were then summed up to a variable called *“line accuracy”* which finally indicated the quality of sketched objects. Second, an algorithm was implemented which automatically measured and quantitatively calculated quality-relevant parameters like “uniformity of shape” or “deviation from optimal shape”. This variable was further distinguished in two subvariables “*uniformity of objects*” and “*shape deviation*” as described below.

4.2.1 Qualitative rating of sketching quality

To estimate the quality of the sketches qualitatively, a category system was developed considering four quality-relevant subcategories. These categories assessed:

a) straightness of sketched lines
b) matching of two lines, which were obviously intended to connect
c) degree of deviation of two lines
d) extent of corrective movements at the end of a line

For each sketched object, a value of 1, 2 or 3 was given in each category, whereas 1 represented “good quality”, 2 “medium quality” and 3 “bad quality”. For a better understanding of the rating system, *Table 3* shows a more detailed description of all categories together with one exemplary anchor-sketch and the accordant rating value. Evaluation of sketching quality was carried out with a computer program which was capable of displaying the sketches in 3D. Consequently, the evaluator was able to freely move the sketch and turn it around the x-, y-, and z-axis. After the evaluation process, the values for each object were aggregated in each category into one overall value labeled *line accuracy*.

4.2.2 Quantitative rating of sketching quality

In order to determine the deviation of the shape of sketched objects from the ideal shape as required by the task definition, an algorithm was implemented. It processed the individual vertices of sketched objects (point-clouds). In a first step, a closely fitting bounding box was calculated. Therefore, a percentile filter was applied in order to omit wild shots. Dimensions of the bounding box were calculated from the minimal and maximal vertex-values on each axis. For the planar shapes (squares and circles) it was also necessary to determine the orientation of the drawing-planes in 3D-space, which was calculated by means of a least squares algorithm. In a second step, the average shortest distance of the sketch vertices to the surface of the ideal shape was calculated. The final value (*shape deviation)*, which indicated how much a sketch deviated from the ideal shape, was calculated from this average distance in relation to the objects’ size (smaller values mean less deviation and better shape). A perfectly drawn shape with no deviation would result in a value of 0; an object entirely out of shape would result in a value of 1.

As a second indicator, the aspect ratio of the sketched objects was also calculated (*“uniformity”,* higher values mean better uniformity). A value of 1 would indicate objects with the same spread in each dimension. A value of 0.5 would represent objects with the smallest dimension (e.g. the depth) being half of the largest dimension (e.g. the width). Both indicators were compared only among objects of the same type.

4.3 Subjective workload

Subjective workload was measured for each trial by applying a questionnaire featuring the 6 subscales (semantic differentials) of the NASA Task Load Index (mental demands, physical demands, temporal demands, own performance, effort and frustration) [HS88]. The scores on these subscales were averaged into an overall score between 0 (low workload) and 100 (high workload).

5. Results

5.1 Comparison of Trials

Participants' performance on 3D-sketching was measured by the dependent variables *line accuracy (4.2.1)*, *uniformity of objects (4.2.2)*, *shape deviation (4.2.2)* and *subjective workload (4.3)*. These variables were collected for each test trial. Descriptive statistics for these dependent variables are shown in *Table 1*. Additionally, time taken to complete the basic sketches was also measured to reveal the efficiency of the 3D-sketching process and to exclude potential speed-accuracy trade-offs.

Table 1: *Means of dependent variables for each trial (standard deviations in parentheses)*

Number of trial	Mean line accuracy	Mean uni-formity	Mean shape deviation	Mean subjective workload	Mean time spent on drafting (s)
1	1.800 (0.037)	0.781 (0.017)	0.126 (0.005)	32.327 (1.713)	170.7 (13.7)
2	1.702 (0.033)	0.812 (0.015)	0.112 (0.005)	31.257 (2.125)	174.2 (15.7)
3	1.641 (0.033)	0.833 (0.013)	0.115 (0.006)	30.285 (2.191)	153.9 (13.6)

In order to analyze performance changes over time (in the course of three test trials), a one-way analysis of variance for repeated measures was performed for each dependent variable. Despite the existence of several dependent variables, a multivariate analysis of variance was not considered, as there were intercorrelations between our four dependent variables. Appropriate use of *F*-test was verified by application of Mauchly statistics, which showed non-significant p-values (*line accuracy p* = 0.576, *uniformity of objects p* = 0.592, *shape deviation p* = 0.747, *time spent on drafting p* = 0.121, *mean subjective workload p* = 0.576), indicating no heterogeneity of covariance.

There were significant effects of test trial on *line accuracy* as measured with the coding scheme [F (2, 44) = 4.274, *p* = 0.013], *uniformity of objects* [F (2, 44) = 4.274, *p* = 0.02] and *shape deviation* as measured with the algorithm [F (2, 44) = 4.274, *p* = 0.009]. No significant effects were found for *mean subjective workload* [F (2, 26) = 4.274, *p* = 0.114]. *Mean time spent on drafting* was 166.3 seconds per object (170.7s for the first trial, 174.2s for the second trial, and 153.9s for the third trial). A repeated-measures ANOVA revealed no significant effects of test trial on drafting time [F (2, 42) = 4.274, *p* = 0.38].

In sum, quantitative analysis of test trial effects suggested significantly increased performance over time, as measured by *line accuracy*, *uniformity of objects* and *shape deviation* (see *Fig. 1-3*), whereas *mean time spent on drafting* did not change over time (see *Fig.4*), which means that participants showed a better performance with each trial in the same amount of time used. Additionally, *subjective workload* appeared to decrease over time, but not significantly (see *Fig 5*).

5.2 Post-hoc analysis of object type

Post-hoc considerations of differences between object types were also of interest. Analysis revealed some differences depending on the type of object, regarding the dependent variables *line accuracy* and *mean time spent on drafting*. For *subjective workload*, no data was collected regarding different types of objects, whereas for *shape deviation* and *uniformity of objects*, comparison of different object types is not appropriate, due to different shapes and dimensions of the objects. Descriptive statistics for *line accuracy* and *mean time spent on drafting* are shown in *Table 2*.

Table 2: *Mean line accuracy and time spent on drafting for each type of object (standard deviations in parentheses)*

Number of trial	Mean line accuracy	Mean time spent on drafting [s]
Circle	1.555 (0.037)	88.3 (12.7)
Ball	1.795 (0.031)	201.8 (17.9)
Square	1.585 (0.036)	148.0 (17.1)
Cube	1.884 (0.042)	208.7 (12.9)

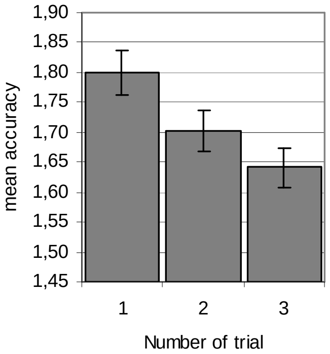


Figure 1: *Mean line accuracy for each trial. Note that higher values mean less accuracy.*

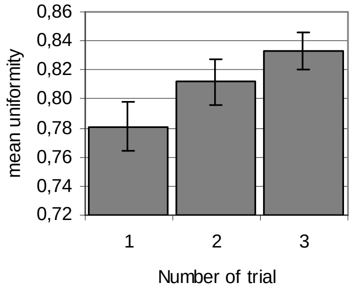
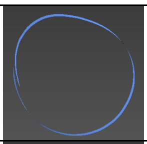
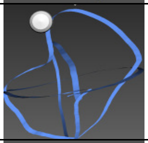
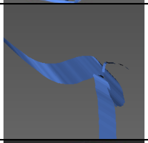
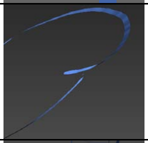
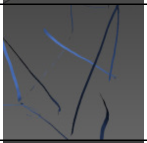
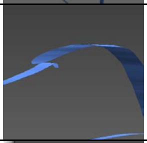
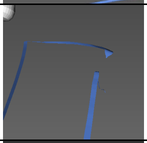
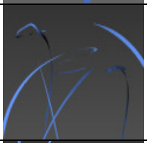
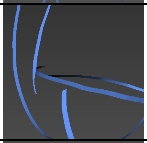
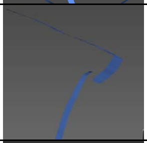
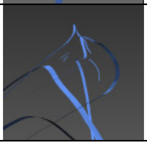


Figure 2: *Mean uniformity for each trial.*

Table 3: *Category system used to evaluate the quality of sketches*

Category	**Description of dimensions of a category**	**Exemplary anchor-sketches**
a) line straightness	1. Lines are drawn quite straight, little or no "waves"	
	2. Lines are quite tremulous, some "waves"	
	3. Lines are very tremulous, many "waves"	
b) matching of two lines	1. Lines are matching (clear contact between lines)	
	2. Lines deviate in one dimension solely (i.e. in x-, y- or z-axis)	
	3. Lines deviate in two or three dimensions	
c) degree of deviation	1. A little deviation between two deviating lines	
	2. A medium deviation between two deviating lines	
	3. A large deviation between two deviating lines	
d) corrective movements	1. No corrective movements at the end of lines	
	2. Little corrective movements at the end of lines	
	3. Large corrective movements at the end of lines	

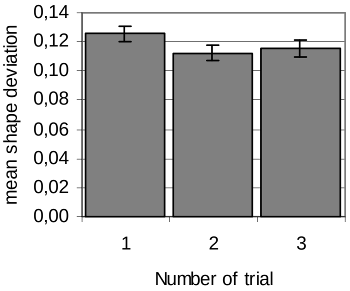


Figure 3: *Mean shape deviation for each trial.*

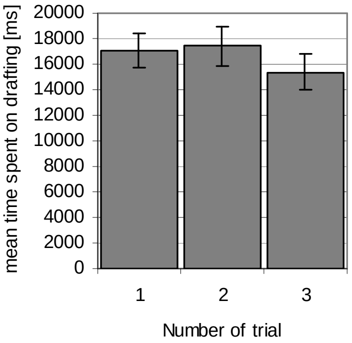


Figure 4: *Mean time spent on drafting for each trial.*

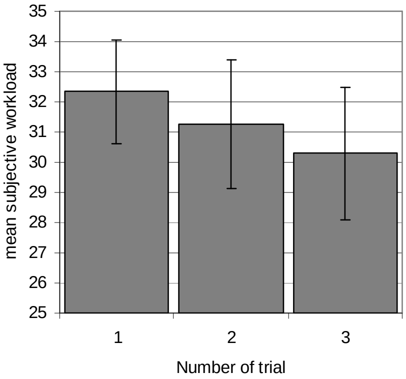


Figure 5: *Mean subjective workload for each trial.*

One-way analyses of variance revealed significant effects for *line accuracy* [F (3, 260) = 18.898. $p < 0.001$] and *mean time spent on drafting* [F (3, 254) = 12.328. $p < 0.001$]. A post hoc Scheffé-test showed that the effect for *line accuracy* was due to significant differences between circle and ball [$p < 0.001$], circle and cube [$p < 0.001$], square and ball [$p = 0.001$] and square and cube [$p < 0.001$]. No significant differences were found when comparing circle and square [$p = 0.96$] or ball and cube [$p = 0.37$] (See *Fig. 6*). For *mean time spent on drafting* the effect was due to significant differences between circle and ball [$p < 0.001$], and between circle and cube [$p < 0.001$]. A Scheffé-test revealed no significant differences between cube and ball [$p = 0.991$], ball and square [$p = 0.11$], square and circle [$p = 0.086$], square and cube [$p = 0.055$] (see *Fig. 6*).

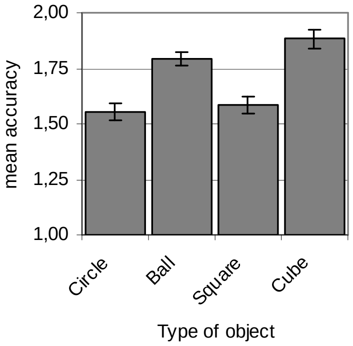


Figure 6: *Mean line accuracy averaged over all three trials for each object. Note that higher values mean less accuracy.*

The results suggest that post-hoc effects in dependent variables were mainly due to different dimensions of the objects. For *line accuracy* the effect depended solely on object dimension, but not on object type. That means that three-dimensional objects are constantly drafted less accurately than two-dimensional objects. A similar effect of dimension was also found regarding the variable *mean time spent on drafting*. Drawing a circle needs significantly less time than drawing a ball, likewise square and cube.

Table 4: *Mean line accuracy and time spent on drafting for 2D and 3D objects (standard deviations in parentheses).*

Object type	Mean line accuracy	Mean time spent on drafting [s]
2D	1.570 (0.036)	118.1 (14.9)
3D	1.840 (0.036)	205.2 (15.4)

For further examination of differences between two- and three-dimensional objects, data for *line accuracy* and *mean time spent on drafting* were aggregated according to the dimension of sketched objects. *Figure 8* and *9* show merged data of 2D-objects (circle and square) and 3D-objects (ball and cube). As the variable object was not manipulated systematically, it was regarded as a “quasi-factor” in our analysis. Therefore, analyses were limited to the descriptive level. Results are shown in *Table 4*.

6. Discussion

The aim of this paper was to investigate the potential of 3D-sketching techniques for supporting design problem-solving activities like form definition and refinement. As experimental paradigm, the assessment of learning curves was chosen. It was hypothesized that 3D-sketching would be an easily learnable skill and that even short training phases will lead to a significantly increasing performance over time. To investigate these questions, we measured 3D-sketching abilities of design and art students during three test trials. The task was to draw four basic geometries with a pen-based 3D-sketching tool. Performance was investigated by measuring mean solution times, mean subjective workload and by qualitatively and quantitatively rating the quality of the sketched shapes.

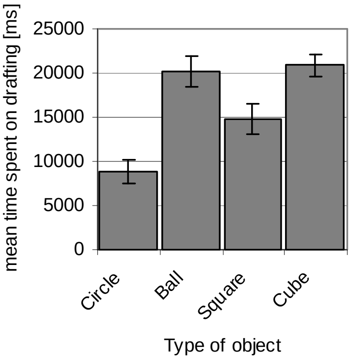


Figure 7: *Mean time spent on drafting averaged over all three trials for each object.*

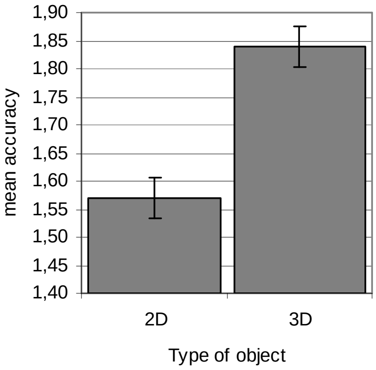


Figure 8: *Mean line accuracy averaged over all three trials for 2D- and 3D-objects. Note that higher values mean less accuracy.*

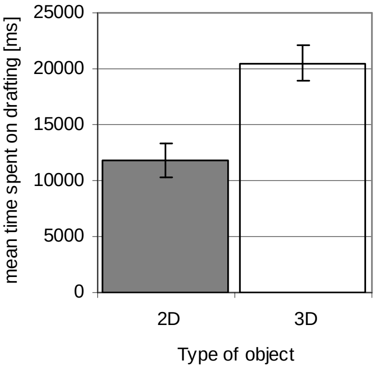


Figure 9: *Mean time spent on drafting averaged over all three trials for 2D- and 3D-objects.*

With respect to performance changes over time (i.e. from trial one to trial three), results suggested a significant enhancement of sketching quality. At the same time, time needed to complete a sketch remained unchanged over time. This insight verifies that there was no underlying speed-accuracy trade-off, which would otherwise result in an increased sketching performance together with a greater amount of time. Higher performance in later trials could rather be attributed to an increased efficiency in sketching and an improved ability in conducting 3D-sketches and that in turn empirically reflects the hypothesized learning effect over time.

With regard to the effect of different object types, post-hoc tests showed significant differences in 3D-sketching performance which can be ascribed to the dimension of the objects. As previously mentioned this effect could only be tested a posteriori and only for the dependent variables line accuracy and mean time spent on drafting. In comparison to the dimension of the objects, the shape of the object seemed to have no influence on sketching performance, because performances for round objects did not significantly differ from angular objects.

For two reasons, performance differences between object types have to be interpreted carefully. First, the quasi-factor object was not operationalized and manipulated as an independent variable. More precisely, it has neither been varied systematically nor randomized over test trials. Consequently, results of the post-hoc tests represent only preliminary results which should be taken as a basis for deriving hypotheses in further quantitative experiments. Therefore, the variables object type and dimension have to be manipulated explicitly in upcoming experiments to draw valid conclusions regarding their effects on 3D-sketching performance over time. Second, differences in accuracy and completion time may result from different factors or from combinations of different factors. On the one hand, differences in quality of sketches between 2D- and 3D-objects could appear as a result of a systematically higher difficulty of the sketching-task itself, as an additional dimension has to be considered by the user. That in turn could result in higher cognitive and sensorimotor demands and in a decreased sketching performance. On the other hand, with an additional dimension, the number of required lines to complete the sketch increases as well, which results in an increased time spent on drafting. Additionally, to create a volumetric shape in three-dimensional space, participants are obliged to make connections between several 2D-objects. Consequently, due to the sensorimotor problems of immersive VR-environments mentioned above, the creation of 3D-shapes may be more error-prone resulting from the limited ability to exactly locate previously drawn object points in space.

The results of the current study raise the question to which extent the loss of performance quality for 3D-objects is due to a) a merely higher manual effort and error-proneness or to b) higher cognitive and sensorimotor demands. The measurement of subjective workload for the sketching-process of 2D- versus 3D-objects could give insight into this question. To further examine the influence of the dimension of the object on sketching performance, upcoming experiments will have to a) consider the dimension of the objects as independent variable and to b) systematically vary system and dimension parameters in isolation to avoid the measurement of confounded effects. Such experiments would then allow for drawing more valid conclusions regarding cognitive and sensorimotor demands of 3D-sketching.

7. Conclusion

As immersive virtual environments are increasingly utilized in industrial processes, the importance of appropriate 3D-interaction techniques is growing, which requires an in-depth analysis of the users' requirements and skills. Former studies mainly concentrated on subjectively measuring the estimated benefit of 3D-interaction techniques and user experience. Although this is an important issue, those studies are neither able to inform about the effects of 3D-interaction techniques on the users' performance nor on the quality of the produced virtual sketches. Additionally, only little is known about the learnability of 3D-interaction techniques yet. The current study tried to address these issues by recording learning curves at three different test trials within a short time interval and by qualitatively and quantitatively assessing the quality of the produced 3D-objects.

The current study contributes to the field of immersive modeling using the example of immersive pen-based sketching. This application was chosen because it resembles the familiar process of pen-and-paper sketching (cf. [Pac05]). The results of this study revealed an improving accuracy and uniformity of sketched objects over time. This provides strong evidence for the hypothesis that users' sensorimotor skills for immersive sketching improve rapidly over time. This is an important finding, regarding the fact that sensorimotor constraints are often mentioned as disturbing factors in user surveys where experience with the system could only be gained in one test trial. Consequently, it could be hypothesized that negative effects in former studies on 3D-sketching techniques might be attributable to low professional skills of the participants in using those techniques and not to the usability of those systems per se. In consequence, to find out which factors will persist in disturbing 3D-modeling after an adequate profession is acquired it is necessary to measure user performance over time. Additionally, more extensive observations should also investigate long-term learning effects (over several weeks) in using 3D-modeling techniques. Finally, future studies should try to realize a combined test-and-training approach to separate the effects of system parameters from the effects of the degree of profession on 3D-modeling performance. A positive side effect of such studies could be to find appropriate training scenarios to foster 3D-modeling skills of professional designers and to integrate them into design education.

Other immersive modeling techniques (e.g. CAD-alike techniques [FASM02; Sto00], virtual clay modeling [KL96] or painting techniques [HSO97; Sch06; SPS01]), which go beyond stroke- and pen-based-techniques, usually also rely on free-hand movements. Therefore, it is to assume that the empirical results of this study can also be extrapolated towards those sophisticated modeling approaches.

8. References

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