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ANALYSIS OF THE USABILITY OF HAND MOTION LANGUAGE IN SHAPE CONCEPTUALIZATION

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ABSTRACT
Conceptualization phase of shape design requires intuitive input and modeling means in order to enable designers to express and visualize their rapidly emerging and changing ideas. In our research, among other things, we have considered hand motions as a communication means for highly-interactive interfaces of the forthcoming computer aided conceptual design systems. We have developed a Hand Motion Language (HML), which incorporates a set of intuitive hand postures and movements often used naturally by designers. Recently, we have developed a pilot implementation of the HML interpretation software and conducted various experiments and tests with it. This paper reports on a study which has been done to determine the usability of the HML in conceptual shape design. In a user study, traditional CAD-based shape modeling and HML-based shape modeling were compared and evaluated in terms of eight criteria: (1) time spent on a specific task, (2) understandability, (3) learnability, (4) operability, (5) general user satisfaction, (6) cognitive load, (7) stimulation and (8) physical comfort. The participants of the user study were asked to perform the same modeling task with commercial CAD software and with the pilot HML–based modeling software. They were also asked to fill in a questionnaire based on their experience with the software. The collected data were processed using statistical methods and semantically analyzed. The results show that the HML-based modeling software performed significantly better in six aspects than conventional CAD modeling, but underperformed from the aspect of physical comfort.

Keywords: Hand Motion Language, shape conceptualization, usability testing

1 INTRODUCTION
The focus of advanced design support research is shifting from detail design to conceptual design and early behavioral simulation. The different application implies different requirements for design support systems. Some of the major issues are creative work and interaction of designers, smart support of creativity, enabling model sharing, real-time behavioral simulation, collaboration of dislocated designers, and handling uncertainty and incompleteness of design concepts. Together with this paradigm shift, truly three-dimensional visualization technologies emerge, which gradually separate graphical input and output from computers. Besides making design systems more knowledge-intensive, growing attention is paid to the human aspects, i.e., the wishes of the customers, end users and designers. To create a basis for the development of Computer Aided Conceptual Design (CACD), new approaches to human-computer interaction (HCI) have been considered, together with smart shape and functional modeling techniques.
The general problem of human-computer interfaces is that they require huge effort in terms of understanding, learning and usage [1]. At the same time, efficient solution of design problems is hindered by ineffective communication. One way of improving the interaction between humans and computers is exploration of new forms of information input and processing. The ultimate goal is to equip the future advanced design support systems with so-called intuitive interfaces, by using e.g. human hand movements, head-and eye movements and voice control as input modalities.
In our current research, we have been investigating the opportunities of using hand motions for shape conceptualization. This research problem is complex and multidisciplinary, and involves several fields of

interest, such as (i) sensor and display technologies, (ii) physical and informational comfort, (iii) information processing, (iv) non conventional modeling and simulation, (v) human perception and cognition, and (vi) design methodology. Our objective is to develop a comprehensive concept and a pilot implementation of a proactive reality environment (PRE) for shape designers. The main characteristics of PRE are (i) applying advanced sensor technologies for situation detection and interpretation, (ii) using natural communication means in multi-modal interfacing, (iii) employing truly spatial modeling, manipulation, imaging and simulation techniques, (iv) implementing the concept of shared resources modeling in terms of humans, artifacts and environments, (iv) relying on smart cooperating agents in terms of system operation, and (v) open architecture and synchronous communication with similar systems. As a constituent of PRE, the authors developed a solution to enable product designers to generate surface patches based on hand motions, and to manipulate these surface patches with a predefined set of hand motions [2].

Our assumption was that HML based modeling is easier, more user-friendly, more intuitive and faster than the Computer Aided Design (CAD) modeling, especially for those product designers, who have difficulties with using CAD systems in the early phases of the design process. Therefore, a user study was designed and conducted to obtain information about the usability of the hand motion based modeling paradigm from a users' point of view. The challenge of our research was to grasp the commonly used terms, like user-friendliness and intuitiveness, and convert them to analyzable and comparable quantitative and qualitative measures. In the context of usability of hand motion based shape design, our main research questions were: (i) what proper criteria can be defined for usability analysis in terms of interpreted hand motions are, (ii) what the right methods for gathering users' opinion about the HML based modeling are, (iii) based on what characteristics can the participants of the study be sorted into comparable groups, and (iv) how the results can be used to develop the forthcoming steps of research. Regarding the usability of HML in conceptual shape design, and compared to traditional CAD, we questioned if (i) HML based modeling is really faster as we assumed, (ii) HML is more intuitive, and (iii) if the users like using the HML interpretation software more. Item (ii) is concerned if the HML is easier to learn and to remember, and the software is easier to be controlled. This paper addresses all of these questions by analyzing the related literature and the results of a user study conducted with fifty participants with a special attention to the users' view on understandability, learnability, operability of the system, general user satisfaction with the system, stimulation, and the influences on the cognitive load and the aspects of physical comfort while the system is used.

The structure of this paper is as follows. Section 2 reports on the result of an investigation of usability definitions and usability analysis methods. In Section 3 the details of the experiment is discussed, which provides the input data for usability analysis of hand motions in conceptual shape design. Section 4 gives an evaluation of the data collected in the experiment. Finally, in Section 5 the results are discussed and in Section 6 conclusions are drawn.

2. RELATED WORK

As a first step, we have conducted a literature review with the goal to study (i) how usability is defined and studied in connection with widely used commercial, and experimental research software, (ii) what kind of qualitative and quantitative measures are used to evaluate usability in the previously mentioned cases, and (iii) what kind of methods exist to test usability with a special attention to human-computer interaction methods. Since our goal was to evaluate HML based modeling on the basis of the pilot implementation of the HML interpreter, we were curious how other researchers approached the problem of usability. More specifically, we were interested whether the well-known and commonly used evaluation methods are relevant for this type of research software too. Furthermore, we were interested in the context the usability was interpreted. Was it defined at software, system or environment level? This is especially important, because our aim was to evaluate an interaction paradigm rather than just the software implementing the paradigm.

There is no common agreement on the definition of usability. Based on our literature review, we learnt that authors all agree that the importance of usability is getting more and more attention, but confusion exists over the actual meaning of the term and its measures. The ISO 9241-11 draft standard defines usability as the "extend to which a product can be used with effectiveness, efficiency and satisfaction in a specified context of use". According to standard ISO/IEC 9126 the term usability is the capability of a product to be used easily, and is related to the capability of the software product to be understood, learned, used and be attractive to the user, when used under specific conditions. Usability is further analyzed in this standard according to understandability, learnability, operability, attractiveness and compliance. This standard also claims that the product attributes required from the point of view of usability depend on the characteristics of the user, task and environment. Therefore, usability is defined in this standard as a property of the overall system.

[3] define measures following the terms used in the definition of usability: effectiveness, efficiency and satisfaction. They define measures of effectiveness by relating the goals of using the system to the accuracy and completeness with which these goals can be achieved. Measures of efficiency are determined by relating the level of effectiveness to the expenditure of resources. The resources may be mental or physical effort, time or financial cost. Finally, measures of satisfaction describe the perceived usability and acceptability of the overall system by its users. According to [4] usability is too abstract to be studied directly, and therefore they divide it into attributes, like learnability – how easy it is to learn the functions of the system, efficiency – the number of tasks per unit of time that the user can perform using the system, user retention over time – it reflects how the users can work with the system after a period of non-usage, .error rate – it addresses the number of errors the user makes while performing the task, and finally satisfaction – it shows the users' subjective impression of the system. A system's usability is not merely the sum of these attributes' values; it is defined as reaching a certain level for each attribute. By reviewing the related literature and legislations, a set of usability factors is identified by [5], which directly impact the end-user. These factors are suitability, installability, functionability, adaptability, ease-of-use, learnability, interoperability, reliability, safety, security, correctness and efficiency. While several authors suggest integrating usability testing into the software design and development processes, the question of how to test usability becomes even more difficult to answer when it comes to research software, which is usually a pilot, experimental software with limited functionality. In these cases, researchers select those important criteria, which help them to prove their hypotheses [6].

Generally, we can say that when testing a system, its performance is measured against pre-defined criteria. To test usability and to collect data for analysis, typically individual users are observed while performing specific tasks with the system [7]. Some of the widely accepted usability testing techniques are the followings. Thinking Aloud Protocol, where participants are asked to vocalize their thoughts, feelings and opinions while interacting with the software. Co-discovery is a type of usability testing where a group of users perform a task together while being observed, simulating typical work processes. Performance measurement tests determine hard, quantitative data. In-field studies concern observation of the users performing their tasks in their usual environment of work. Questionnaires and interview based protocols are used to ask direct questions from the users about the system. While inquiry methods can be also used to measure various usability attributes, their most common use relates to measurement of user satisfaction. A known technique for measuring user satisfaction and hence assess user perceived software quality is through the Software Usability Measurement Inventory (SUMI). SUMI results are analyzed into five sub-scales, namely, affect, efficiency, helpfulness, control and learnability.

In summary, we can say that there is no common agreement on the definitions, measures and testing methods of usability. Although some definitions exist in widely accepted standards, they reflect different interpretations, and researchers use them based on their own reasoning to derive measures from them. On the other hand, these standardized definitions and the most common measures and testing methods were designed to serve the needs of commercial software developers, and no directions are given to researchers working with less defined prototypes. However, researchers have tried to make use of those measures and methods which make sense in their own field of interest. Our approach is similar, and we focus on two major issues regarding the usability of hand motion based modeling: (1) task completion time and (2) user satisfaction. While task completion time can be measured in simply, user satisfaction is more complicated to be measured. For this purpose, we selected to use a questionnaire-based method. The questionnaire was constructed based on SUMI, as it is the most commonly used questionnaire for gathering users' opinion, but our questionnaire also incorporates some specific questions related to hand motion based modeling.

Furthermore, as it was suggested by several authors, we considered usability as a system property, which covers all the hardware and software aspects and the interaction method as well.
In the next section first we introduce our assumptions and hypotheses related to the usability testing of hand motion based modeling, and then we elaborate on (i) the description of the testing environment, (ii) the design and (iii) the results of the user study.

3. EXPERIMENT

In this section, we report on the design, conduct and results of a user study, which was done in order to evaluate the usability of hand motions in conceptual shape design. We assumed that the HML based modeling gives a novel and intuitive platform for product designers, who think of computers as necessary equipment in their work, but actually they have reluctance to use it. We would like to prove, that HML based modeling performs better than traditional CAD in conceptual design tasks. First of all, it means that products could be modeled faster, but we also believe that it does not ruin the creativity and enthusiasm of designers when using this method. Actually, we believe that it is exactly the opposite, and designers would be willing to use this system mainly because it supports creativity in their work. However, because of the novelty of hand motion based input in shape design, there was no guarantee for the correctness of this assumption, and the purpose of the user study was to prove it, or at least gain some information about the abovementioned aspects.

3.1 Research hypotheses

Because we wanted to compare the hand motion based interaction paradigm with the conventional graphical interaction paradigms, it seemed to be logical to select some of the widely used commercial CAD software, which are used in the industry and academy as well, as a basis for comparison. When we refer to the HML technique and CAD, we always mean it on a system level, which integrates the necessary hardware (input device, visualization device, etc.), the software (HML interpreter, shape modeler) and most importantly the interaction method itself (hand motions, keyboard- and mouse control). With regards to HML based modeling, our hypotheses were that (1) users can conceptualize shapes much faster with the HML, (2) HML is more intuitive both for novel and expert CAD users, (3) HML is more attractive, which means that people are more enthusiastic to use it, (4) HML is mainly attractive for those users, who has no experience with CAD, and as an obvious disadvantage that (5) HML is more tiring physically, because of its active nature, but on the other hand it is less tiring mentally (actually, it is more stimulating).
To be able to evaluate the abovementioned assumptions and to prove our hypotheses, several criteria were defined. To demonstrate the fastness of our method, we decided to measure the time the users spent with both systems and compare them, and see if there is any relevant difference between them. For analyzing the intuitiveness of the HML based modeling method, the criteria of understandability, learnability, and operability were introduced. To see if people would like to use such a system, the criteria of satisfaction was defined. Finally, to find out the mental and physical involvement of people when using hand motions, in other words, how tired they become both mentally and physically, criteria were set for cognitive load and physical comfort.

3.2 Design of the experiment

The user study was conducted with fifty participants, who were different in their gender and age, and they either had experience with computers and CAD software or not. The characteristics of the participants are shown in Table 1. The participants were asked to perform the same modeling task with the pilot hand motion modeling software and a commercial CAD software. Video recording and questionnaires were used as data collection instruments. Each session was recorded on videotape, and the participants were asked to fill out two types of questionnaires. The pre-study questionnaire contained information about the participant, such as gender, age, educational background, level of general computer experience and level of experience with any CAD software. Based on these information, comparable groups were formed, such as male vs. female participants, participants with beginner or intermediate level vs. participants with advanced level of general computer experience, participants without any CAD experience vs. participants with CAD experience, and as sub-groups of participants with CAD experience, participants with beginner or intermediate level vs. participants with advanced level of CAD experience.

Table 1. Characteristics of user study participants

Gender	Age	General computer experience	Prior knowledge to CAD software
37 male	Min. 18 and max. 54	10 beginner or intermediate	36 yes
13 female	Average 26.52	40 advanced	14 no

The post-study questionnaire was related to the modeling paradigm the participants used during the experiment, and reflected their experience and opinion with them. A separate post-study questionnaire was filled out for both HML based modeling and for CAD modeling. The questionnaire contained twenty statements and used a forced choice Likert-scale with four answers: strongly agree, agree, disagree and strongly disagree. A full list of the questions can be seen in Table 2. The first and the last question was a general question with regards to the environment and to the achieved result. The other questions were selected from the Software Usability Measurement Inventory (SUMI) sample questionnaire with a view to the previously formed categories: understandability, learnability, satisfaction, operability, cognitive load, stimulation and physical comfort. Those questions were disregarded which referred to documentation and help, to the design and usage of graphical controls, and to the usage of keyboard and mouse. These questions are meaningless in the case of HML based modeling. On the other hand, some questions were added to the questionnaire regarding physical comfort, which topic was not covered by SUMI. Three questions combined together form a category, e.g. the category learnability involves questions no. 5, 12 and 16. Exceptions are the category cognitive load, which contains two questions, and stimulation, which has only one question.

3.3 The testing environment

For the purposes of our tests, the 5DT dataglove was used to measure the flexion of the fingers. Usually we prefer to use non-contact technologies for the measurement of hand motions, because in these cases the user is not connected to the computer with cables. However, unlike the aforementioned passive systems, the dataglove provides continuous input for the HML interpreter, and therefore gives a solid platform for testing purposes. To measure the three-dimensional position of the hands, a Polhemus Patriot magnetic position tracker was attached to the back of each dataglove. Participants wore 3D glasses to support navigation in the virtual environment. (Figure 1.right)

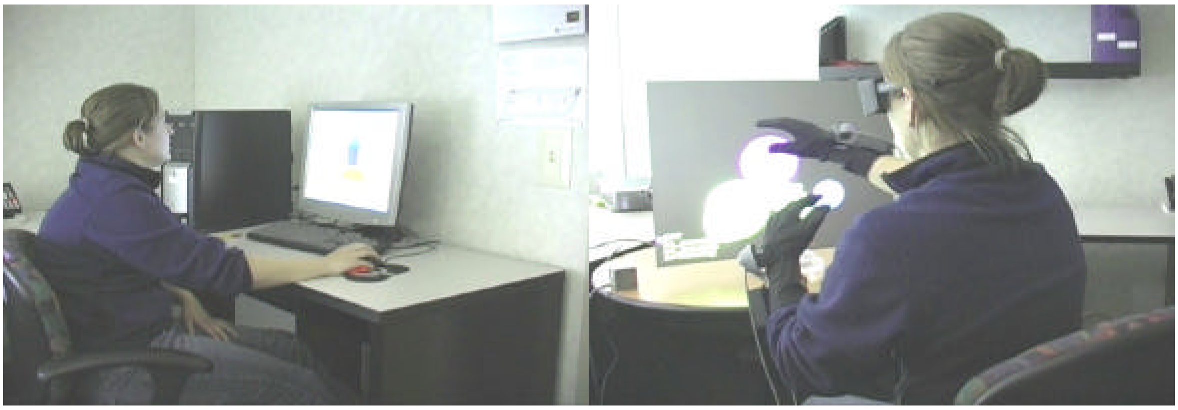


Figure 1. (left) Testing environment CAD, (right) testing environment HML

The HML interpreter [8], which was developed earlier, was integrated into the VR Juggler environment [9]. VR Juggler provides a virtual platform for virtual reality application development. Applications using

Juggler technology are highly flexible, run on many operating systems, and support many I/O devices. The HML interpreter recognizes different hand motions defined in [10], and converts them to geometric manipulation commands or to surface patches, and this way enables the fast generation of virtual objects. In the case of the CAD environment, a conventional desktop computer was available for studying interaction and two-dimensional monitor for providing visual feedback (Figure 1.left). For object modeling, SolidWorks, SolidEdge and Autodesk software was at the disposal. Participants could select one of the available software in the case of the CAD environment, which they are the most familiar with. With providing several options, our goal was to avoid misleading conclusions about time, because the experience with the software influences the time a participant spends with it.

3.4 Conducting the experiment

The protocol of the user study was the following. First the participant filled out the pre-study questionnaire. Then he/she was explained what was going to happen in the experiment. He/she was asked then to flip a coin in order to randomly select the first software to be used. If it had turned out heads, the participant started with the HML based modeling system, if tails, with the CAD system. In each case it was explained shortly how to use the hand motion based modeling system. If the participant did not have any experience with any of the available CAD systems, he/she was explained how to perform the given task in SolidWorks. Each questionnaire was filled out directly after the session either with the HML based modeler or the CAD modeler. The task was to draw a hill-like surface, to build a tower out of three given objects and put the tower on the top of the hill. The task was designed in a way, that it contains all of the basic manipulation tasks which are used during modeling, such as positioning and rotating. For generating the hill, a freeform surface should have been created. The participants were told that accuracy of the model is not important, and it can be in any direction and orientation. They could create any kind of object which looks like a tower on the hill using their imagination. Each session was recorded with a digital video camera to be able to precisely measure the time what participants spent with the task.

4. RESULTS AND ANALYSIS

This section evaluates and discusses the results of the user study. There are three main aspects to be evaluated, namely (i) the time spent on the task users were asked to perform, (ii) differences in the predefined categories comparing HML based modeling and conventional CAD modeling according to the post-study questionnaire, and (ii) differences in the groups formed based on the pre-study questionnaire. Table 2 shows the statements of the post-study questionnaire and the mean value of the given answers.

Table 2. Evaluation of the post-study questionnaires

Question	Mean Value CAD	Mean Value HML
1. I liked using this environment very much	2.69	3.02
2. Working with this environment did not make me physically tired	3.29	2.65
3. I sometimes wondered if I was using the right command	3.18	2.57
4. Working with this environment is mentally stimulating	2.76	3.12
5. It took me too long to learn the controlling commands	2.55	1.82
6. It was easy to make the application do exactly what I wanted	2.35	2.23
7. I enjoyed my session with this ap plication	2.80	3.35
8. There have been times in using this environment when I felt tense	2.47	2.37
9. I always knew what to do next	2.39	2.92
10. This application behaves in a way which cannot be understood	2.55	2.76
11. I would recommend this to friends or colleagues	2.63	2.96
12. It easy to forget how to do things with this application	2.84	1.88
13. When using the environment, I felt pain in my shoulder or neck	1.69	1.94
14. I would not like to use this application every day	2.47	2.37
15. There are too many steps required to get something work	2.61	1.82

16. Learning to operate this application is easy	2.55	3.04
17. Using this environment is frustrating	2.49	2.45
18. Tasks can be performed in a straightforward manner using this application	2.55	2.88
19. When using the environment, I felt pain in my hands or in my fingers	1.53	1.90
20. I think I have completed the given task well	2.82	2.63

4.1 Time

Participants spent 374.86s in average with performing the task with CAD and 266.62s in average with the HML based modeler. The Wilcoxon signed-rank test was used for comparative analysis. The result of the test shows that the time spent on the task using CAD was significantly higher ($p < .05$, $r = -.29$) than the time spent when HML was used.

4.2 Categories

Seven categories were formed by adding positive converted statements. The categories are the followings: understandability (statement 3, 9 and 10), learnability (5, 12, 16), satisfaction (7, 11, 14), operability (6, 15, 18), cognitive load (8, 17), stimulation (4) and physical comfort (2, 13, 19). The results are shown in Figure 2.

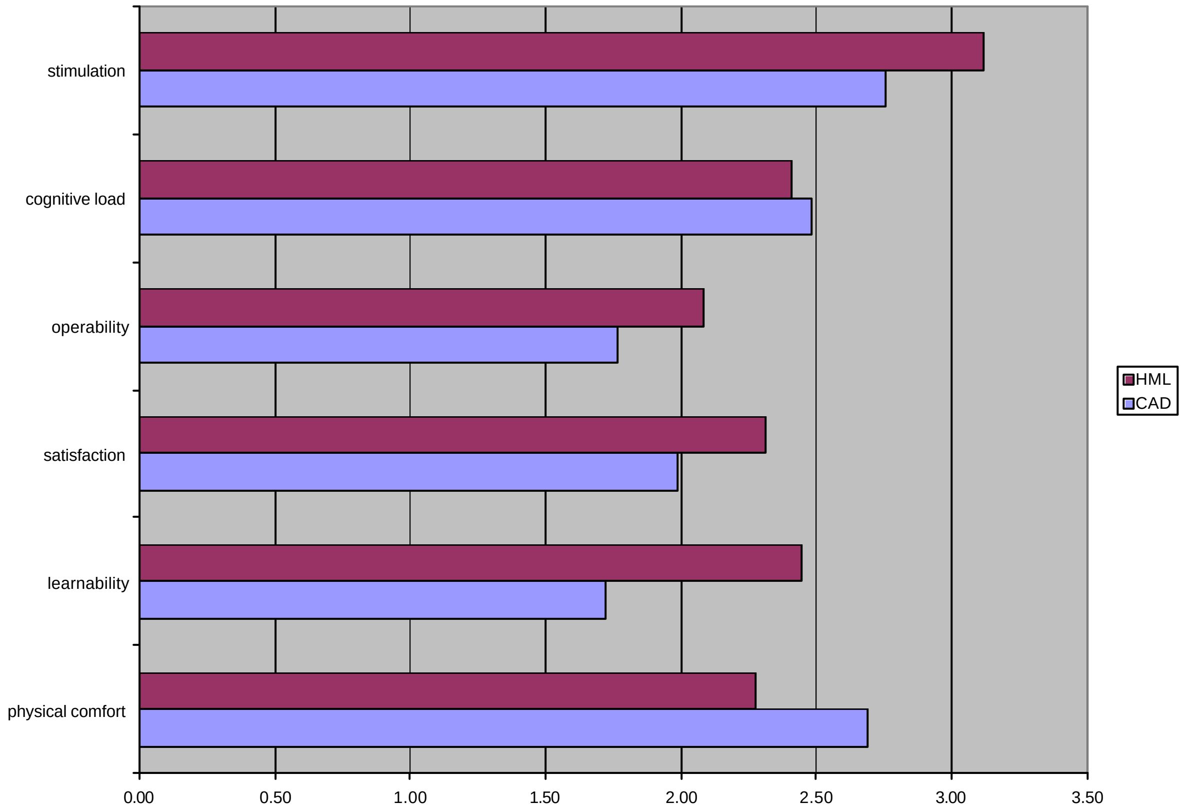


Figure 2. Comparison of HML and CAD based on categories

Results are summarized in the followings:

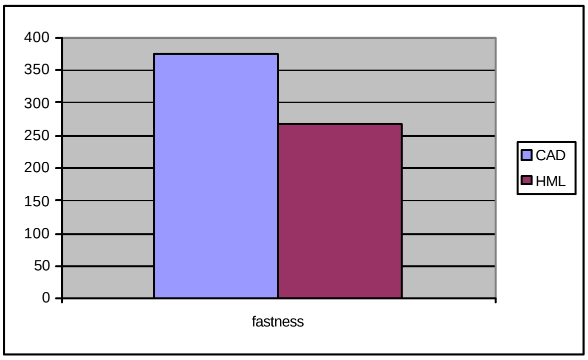
- HML based modeling is easier to understand ($p < .01$, $r = -.43$), which means that users (i) are sure that they are using the right command more often, (ii) are more likely to know what to do next, and (iii) understand the behavior of the HML based modeler more.

- HML based modeling is easier to be learnt ($p < .001$, $r = -.67$), which means that users (i) take less time to learn the controlling commands, (ii) are less likely to forget how to do things with the HML based modeler, and (iii) think it is easier to learn how to operate the HML based modeler.
- Users are more satisfied ($p < .01$, $r = -.42$) with the HML based modeler, which means that users (i) enjoy their session with it more, (ii) would recommend it to friends or colleagues more often, and (iii) would like to use it on a daily basis more often.
- The HML based modeler is easier to operate ($p < .05$, $r = -.33$), which means that (i) it is easier to make this application do exactly what the users wanted, (ii) there are fewer steps required to get something work, and (iii) tasks can be performed in a more straightforward manner.
- There is no difference found in the cognitive load on the user while operating the HML based modeler or the CAD modeler. It means that users are equally likely to feel tense or frustrated when using them.
- HML based modeling is more stimulating ($p < .01$, $r = -.44$).
- CAD is less comfortable physically ($p < .001$, $r = -.58$), which means that users (i) become more tired when using it, (ii) and are more likely to feel pain in their shoulders, necks, hands and fingers.

4.3 Groups

The seven categories for both CAD and HML were divided in groups based on the pre-study questionnaire. The groups were formed according to gender, general computer experience and experience with CAD software. A comparative analysis was performed with the Mann-Whitney test in order to look for differences between the groups. Results show that there were no significant differences between men and women, and between participants with beginner or intermediate general computer experience and with advanced general computer experience. Some significant results were found between participants with and without prior knowledge to CAD software. Participants with a prior knowledge to CAD software scored higher in the categories satisfaction ($p < .01$, $r = -.47$) and operability ($p < .05$, $r = -.35$) of HML, than participants without prior knowledge.

4.4 Discussion



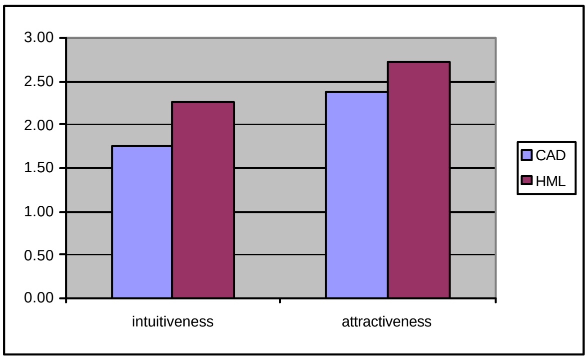


Figure 3. Comparison of CAD and HML based modeling according to fastness (left), intuitiveness and attractiveness (right)

The results were compared to our hypotheses on fastness, intuitiveness and attractiveness. We assumed that the HML based modeler performs better in the aforementioned categories. Speed of use was measured by the time spent on the task the users had to perform. Intuitiveness was measured by combining the categories learnability and operability, and attractiveness was measured by the categories satisfaction and stimulation. Together with the general satisfaction with the HML based modeling paradigm, which shows to what extent the designers are willing to use the software, stimulation is also important in the conceptualization phase of design. Figure 3 shows that when compared to conventional CAD (i) HML based modeling is faster, (ii) more intuitive and (iii) more attractive.

5. CONCLUSIONS

Based on the results of the user study, we can conclude that participants judged the HML method to be better than traditional CAD for conceptual shape design. Especially the category of learnability showed significant difference in favor of HML based modeling, but the categories of operability, stimulation and satisfaction showed considerable differences as well. Participants (1) were significantly faster in creating conceptual shapes, (2) found the hand motion input more intuitive and (3) were more satisfied, which means that they are more willing to use our system. It turned out that HML based modeling makes people more tired physically than traditional CAD. However, opposite to what we expected, it turned out that the experienced CAD users found HML based modeling to be better in the categories of satisfaction and operability than the novel CAD users. An explanation for this may be the ability of the expert CAD users for better judgment of modeling methods because of their prior knowledge. Since novel users got only a short explanation how to use the CAD software, more precisely, they received only those pieces of information which they needed in order to be able to perform the task, they had much less insight than expert users.

It could also be observed that participants could create a variety of shapes with the HML based modeling method using their fantasy. They did not simply try to copy the sample shape, which was shown to them, but created different ones based on their own imaginations (Figure 5). On the other hand, when using CAD, they mostly concentrated on the successful completion of the task, and they did not care about the originality of their work. Therefore, the resulting shapes were very similar to each other (Figure 4). In the conceptualization phase of product design, it is very important to be creative and to generate a group of new shapes, from which one can be selected for further elaboration.

We also observed that different type of people reacted differently on the modeling methods. More precisely, it seemed that people, who happen to be more active, creative and curious, liked the HML more than passive people, and they could work with software better. On the other hand, nervous type of people had difficulties to control the HML based modeling software, because of their fast hand movements and their sudden emotional reactions when something went wrong. These observations suggest that another study should be done which implies the personality analysis of the users.

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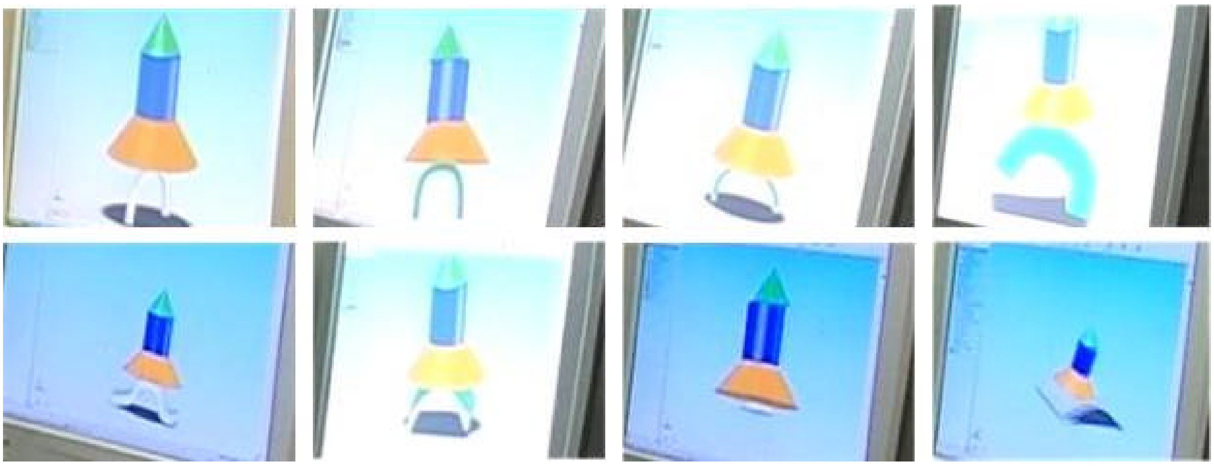

Figure 4. Some example shapes created with CAD software

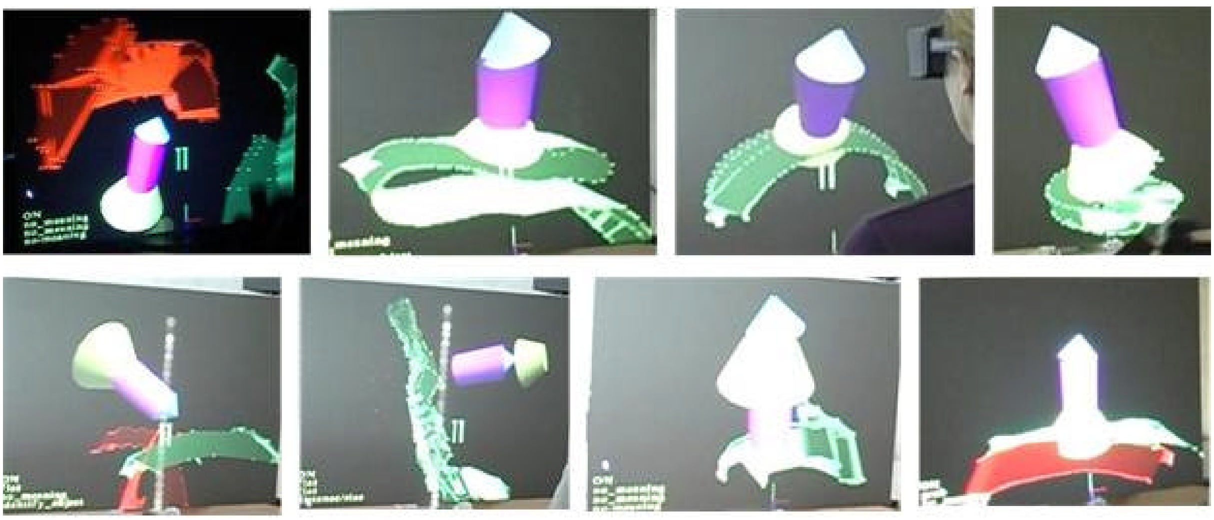

Figure 5. Some example shapes created with the HML based modeler