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Designing with computer and sketches[1]

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We investigated whether and, if so, for what reason, problem solving in design may be supported by "external approaches", especially sketching. An experimental study with 74 undergraduates analyses whether sketching before and/or during Computer Aided Design (CAD) improves the quality of solutions, reduces time taken as well as the number of processing steps in CAD, by offering the opportunity to test the functions designed. In spite of additional sketching time, the total time taken is significantly reduced for the more complex task analysed. This can be explained by the reduction of the number of processing steps needed. These experimental results verify the perceived utility of sketching before and during Computer Aided Design, confirmed in a questionnaire study with more than 100 experienced engineering designers.

Key words: Design problem solving, engineering design, sketching

Designing, in the sense of designing new objects, is defined as "complete and creative thinking ahead of a technical object … and creating all effective basics for its material realization" (Bock, 1955, 504f). It is a form of problem solving in design.

Problem solving in design needs a structure of applicable and complete problem representations, assisting the generation of a solution (Adelson, 1981; Hegarty, 1991; Hacker, 1998). The structure and the acquisition of those representations can be supported and accelerated by "external conceptual design activity" (Hacker & Matern, 1979; Hegarty & Just, 1993; Klauer, 1993, 1995; Römer, Leinert & Sachse, 2001): Through sketching and modelling, a mental model can be developed, specified and corrected (Viebahn, 1996; Purcell & Gero, 1998; McGown, Green & Rodgers, 1998). Frick & Müller (1990) have pointed out that external representations of thoughts support both synthesis and the development of solutions.

Neglecting external procedures can lead to difficulties in generating a successful development process, a process which concerns mental representations of the problem and the mental operations. Furthermore, it can lead to a reduced gain from experience (Leinert, Römer & Sachse, 1999).

Sketching and modelling have multiple functions within the designing process. They serve as generalisations of complex tasks and their varied correlations (working structure), as tools for planning and controlling as well as for reflection. Systematically questioning experienced designers has shown that these forms of external support may also serve as aids to analysis, as instruments of evaluation, as supports for solution-finding, and as storage and communication aids (Sachse, Leinert, Sundin & Hacker, 1999).

In field studies, various external approaches were tested with respect to their functions and time of use within the process, as reported by designers (Leinert, Römer & Sachse, 1999). Simple material models and rough sketches can be produced with little effort during the designing process. They also simplify the tasks involved. Complex models demand an additional production effort besides the main designing process but also a match with parts of the final product as far as physical or informational aspects are concerned (models of original materials, prototypes, construction drawings). It turned out that none of the external procedures examined met all functions and therefore could not be used in all phases of the designing

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process. According to the designers, free-hand sketching has the widest range of functions.

A "sketch is a not necessarily scaled, mainly free-hand drawn drawing" (DIN 199-1, 1996, 3). It is a first, often brief embodiment of a design or a premonition, a vague idea of a thought. It can both relieve the working-memory as well as enhance communication among designers themselves or between designers and the customer (Ferguson, 1993; McGown, Green & Rodgers, 1998).

Sketching and then working with and on the sketch produced do not merely have the storage-relieving and therefore memory-relieving effects identified in the literature (Muthig & Schönpflug, 1981; Schönpflug, 1986; Klauer, 1993; Dörner, 1994). On the one hand, solutions are made concrete by sketching, and on the other hand, sketching may serve to differentiate, control and correct these solutions (Sachse, Hacker, Leinert & Riemer, 1999).

Furthermore, it can be assumed that besides reverting to a sketch and working further on design problems, the *process* of sketching already has a supporting effect. Immediate feedback, for example, by looking at the developing sketch, is as beneficial as the reduction of complexity, which is a prerequisite for finding solutions. Sketching, as an external fixation of ideas, could force the designer, from the start, to define his or her ideas more precisely, as well as to control them. At the same time, sketching reduces ambiguity and vagueness. The structure and acquisition of solution-assisting mental representations can be accelerated by pictorial forms (sketches, drawings) (Rowe, 1987; Fish & Scrivener, 1990; Leinert, Römer & Sachse, 1999). The correctness and distinctness of the mental representations determine both the quality of the cognitive processes based on these mental representations and the quality of the actions orientated by them. In a questionnaire study, 55% of 106 experienced designers stated they regularly or always make sketches while preparing computer work; and 36% stated they used sketches even during CAD. The sketches were interpreted by the designers as a support for demand classification for concept development as well as for making solutions more concrete, for communication and for remembering important details (Römer, Weißhahn, Hacker & Pache, 2001). These functions justify the notion that the fixing of innovative thoughts during sketching leads to a relief of working-memory (cf. Ullman, Wood & Craig, 1990; Lawson, 1994; Pearson, Logie & Green, 1996; Purcell & Gero, 1998).

We will therefore test in an experimental study whether or not sketching, in connection with CAD, actually provides the advantages identified in the questionnaire study and what these advantages consist of.

An experimental procedure is necessary in order to ensure identical tasks under identical conditions for all experimental subjects – in contrast to the questionnaire used in the field study – and therefore enable evaluation of performance. For practical reasons of cost, the sample was not composed of engineers or software developers. Instead a sample of undergraduates was drawn and an embodiment task was developed which the subjects were to handle on the computer.

Main questions

The subject of this study is the examination of the supporting effects of sketching for the development of technical objects on the computer. In an experiment which simulated this development activity, we studied the entire process, starting with the analysis of demands, through to the production of a functioning solution. We asked the following questions:

1. Does sketching increase the potential output during analysis of the problem and development of the solution as compared to working on the computer without sketching? Also what kinds of process-criteria and result-criteria are altered by additional sketching and in what way?
2. In the case of sketching, do the expected differences, in both process and result, depend on the complexity of the problem?
3. What advantages and disadvantages of working with or without sketching are reported by subjects?

Based on the survey results described above and assumptions made in the literature, we postulated the folowing:

1. By sketching before and during drawing on the computer, inspite of the additional time required for sketching, less working time is needed as a whole.
2. This time saving is due to a lower number of total working steps because the testing and correction of working steps can be substantially reduced.
3. Through additional sketching, a better quality solution can be reached.
4. The differences expected in hypotheses 1 through 3 will only be found with complex problems, not with easy ones.
5. Most of the subjects would report a supporting role for sketches in the process of solving the more complex problem.

Method

Subjects

The sample consisted of 76 undergraduates from different faculties of the Technical University of Dresden. Given a sample of this size, from a statistical point of view, large to medium level impacts should be detectable. The data evaluated were based on a sample of 76 subjects. The data for two cases had to be dropped from the analysis because of their familiarity with the specific computer programme used. The remaining participants formed a homogeneous group with similar knowledge at the beginning of the experiment. The average age of the participants (65% of whom were female) was 25 years. Using random sampling, two sub-samples were formed. In a preliminary test, the samples had been checked as regards their equivalence (as stated below): no accumulation of expertise could be found.

The number of subjects was sufficient for a 2×2 factorial measurement with repeated measures on one factor, an α-level of 0.05, a test strength of $1-\beta = 0.8$ and an expected medium impact ($f = 0.30$) (Cohen, 1988).

Task

Two problems, varying in difficulty, which had been designed especially for this purpose, were presented to the subjects. A solution had to be developed that would allow an object (a ball) to move from the left side of the screen in a "pipe box" to the right side of the screen (problem requirements: see Figure 1). In the instructions, clear starting conditions and objectives were given; only one starting condition and one objective was assigned for each problem. The software used allowed different solutions. In an inventory list, the subjects had 45 different kinds of objects (operators) at their disposal. Information about the starting conditions, means and methods of the solution (information about how the system operates and about features and characteristics of each object) were presented in written instructions.

The subjects in one sub-sample received additional instructions to develop their ideas for solutions by sketching and then realizing them on the computer. The instructions given to the other group did not include this additional request.

Material

For the experiment, we used the software "The Incredible Machine"[2] (TIM). Under the simplified conditions of an experimental study, the programme enables the user to develop problem requirements, to record solution steps and to analyse individual procedures. This programme simulates a surrounding in which devices for handling mobile objects can be developed and tested (Göker, 1996). In addition, the programm enables the user to make trials. At any time during the process the solution can be tested for efficiency and, if necessary, can be corrected by the user.

The problems developed were submitted to a theoretical problem analysis. Here, the different problems and intermediate phases were analysed. The quantity of intermediate phases depends mainly on the choice of available objects in TIM. Whereas some objects enable a solution using only a small number of steps, other objects force the subject to use additional objects and therefore additional steps. Based on this principle, all possible useful intermediate phases were listed. This enabled us to describe not only the structure and constitution of the problems, but also the requirements to be met by the subjects. Through this procedure, we were able to establish intended complexity and differences in demands (Schroda, Leinert & Sachse, 1996).

Pilot study checking group homogenity

Before starting work on the problem, all subjects were given an introduction to the computer programme. In addition, they were asked to work through the written instruction for the features and characteristics of the objects. After having concluded this standardized training period, all subjects solved a problem task which was less complicated than the tasks that followed. The objective was to gain experience with the programme. The criterion for the actual start of the test was having successfully completed

Problem 1 **Problem 2**

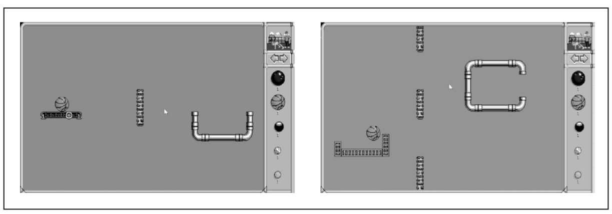

Figure 1: Problem tasks

partial problems (Problem 1)
– move and guide object (ball)
– get over obstacle
– move ball into the "basket"

partial problems (Problem 2)
– "free" ball from device, hereby moving the ball further
– get over obstacle
– guide ball
– gain height
– change direction and move ball into "basket"

2 © Sierra On-Line Inc.

this task. Following this training period, all participants had reached a comparable level of knowledge concerning the characteristics of the objects and the structure of the computer programme. To ensure the formation of similar sub-samples, differences with respect to all dependent variables for the solution to the training task were tested using t-tests for independent samples. There were no significant differences between the two groups. In addition, the working-memory capacity of the subjects was tested with the computing span test (cf. Hacker & Sieler, 1997). Here also the differences between the groups were compared. There were no significant differences here either. Homogeneous task-relevant performance prerequisites can therefore be assumed.

Experimental design

In the main part of the studies, a 2×2 design was used. The group factor A concerned the working conditions, the repetition factor B concerned the problem complexity. The group factor was divided as follows:

a) designing with the computer with the option of "trying" (testing the attempted solution) via sketching,
b) designing with the computer with the possibility of "trying" to judge the attempted solution, without sketching.

All subjects dealt with problem 1 first and then with problem 2. We did not attempt to balance the order of presentation because of an interest in the participants gaining expertise by using the computer programme with a simple problem and therefore a lower break-off rate for the second and more complex problem task. This was acceptable as the problem task had been designed in a way which allowed practice effects to occur only within the computer programme. The likelihood of a transfer of problem-solving knowledge from task 1 to task 2 was very low because of the different paths to solution and partial goals involved in each case. In the most unfavourable case, the more complex task would be favoured through positive transfer. Therefore, the effect of a difference in complexity would be reduced. If significant effects of complexity were still found this should reinforce confidence in the strength of such an effect.

The solutions were recorded on video and assessed using a category system which had been verified in an earlier test (cf. Sachse, 1999). In order to operationalise the process criteria, programme-specific functions were added for this test. An expert at TIM counted the number of steps used by the subjects. In addition, all actions leading to the solution were recorded by the computer.

Dependent variables

Both process criteria and result criteria were recorded as dependent variables. The process criteria analysed are a) complete solution steps which a subject needs take in order to conclude the task, and b) the characteristics of these steps. These working steps are defined in Table 2.

Both the quality of the solution as well as the time to solution were used as dependent variables. Quality was defined as the number of objects needed to produce a functioning solution. Using a problem space analysis (cf.,

Table 1: Experimental design (2×2 mixed (inter-group/repetition) design, n = 74)

inter-group Factor A: conditions of working the task	*repetitive* Factor B: complexity of the tasks Problem 1 (medium complexity)	 Problem 2 (high complexity)
a) supported problem analysis by sketching and constructing with the computer with possible "trying"	37	
b) problem analysis and constructing with the computer with possible "trying"	37	

Table 2: Types of steps and their operationalisation

Providing steps	An object is taken out of the available supply and provided for further construction.
Adjustment steps	An object is adjusted on the monitor to the already existing conditions or it is adapted to the given demands. It is, e.g., turned, shortened or prolonged.
Repeating steps	An already existing solution idea is renewed after it has been rejected for a short time. Therefore, one or more objects are put back into a previous order.
Rejecting steps	An object is permanently rejected because it does not seem to be a feasible solution. It is removed from the screen.
Positioning steps	An object is put into another position on the screen. A different structure of the solution idea is derived from this.
Trying steps	The functioning of the design is tested.

problem task), the most efficient solutions and the matching object numbers were found, so that a reasonably comparative value was available for these variables.

The process and result criteria were examined via an ANOVA with repeated measures on the complexity factor (medium/high).

Results

As expected, the numbers of elements used, the time used to solve the problem and the number of steps were higher for the more complex problem. The ANOVA shows significant effects for variables relating to the process of solution and for the complexity of the problem (F-values between 15.1 and 74.7 with p = .01; Table 3), as well as a significant interaction between the complexity of the problem and sketching for the total number of steps (F = 4.80; df = 1; p = .03) – and also for adjustment and attempts – and time to solution (F = 5.11; df = 1; p = .03). Subsequently individual comparisons were undertaken (cf. Table 4).

Table 3: Demand differences of the problems

Variable	F- value; df-value; p-value
Total number of solution steps	63.69; 1; 72; p. 01
Providing steps	51.69; 1; 72; p. 01
Adjustment steps	48.71; 1; 72; p. 01
Repeating steps	15.13; 1; 72; p. 01
Rejecting steps	33.19; 1; 72; p. 01
Positioning steps	33.12; 1; 72; p. 01
Trying steps	74.68; 1; 72; p. 01
Solution time	53.98; 1; 72; p. 01
Number of objects	48.48; 1; 72; p. 01

Means and standard error are shown in Table 4

A more detailed breakdown is provided in Table 4. This presents the results of the impact of sketching on the two problems differing in levels of complexity. It can be seen that sketching has no significant impact on less complex tasks. However, the time taken to reach a solution and the total number of steps differ significantly for more complex problems. Solution quality, defined here as the number of objects used for the production of a functioning solution, was greater when sketching was allowed but the difference did not reach statistical significance. The small number of "trying" steps (trying out; testing) and correcting steps (rejections, adjustments) acount for the smaller overall number of steps with sketching.

Thus, the hypotheses set out in the introduction, based on the anticipated supportive effects of sketching for complex problems were confirmed with the exception of the impact on solution quality. The significant test results indicate a medium impact in the ex-post-determination.

Statements provided in the interview showed that the majority of subjects in the sketching condition (70%) did not think they needed the sketches for the less complex task, whereas they did for the more complex task. These subjects perceived a supporting effect of additional sketching mainly for analysis of the circumstances given (59%), for structuring the solution (68%) and for planning a path to the solution (32%). Sketching was said to help develop a preconceived idea and had a memory-relieving impact throughout the whole process.

However, sketching did not help them to assess the connection between cause and effect in the sense of evaluating solutions. This occurred instead through the possibility, made available through the computer programme, of trying out solutions. This made it possible to recognize the functioning (proportions, kinematic process) and the characteristics of the objects as well as to estimate the effects of mechanical laws.

Table 4: Means and their standard error for performance and procedure features

Dependent variables	Medium complexity-problem with sketch	without sketch	Significance	High complexity-problem With sketch	without sketch	Significance	Effect size
Result criteria							
– Solution time	20.8 ± 2.2	18.5 ± 2.2	ns	36.5 ± 3.2	48.8 ± 4.9	.05	0.51
– Quality (object number)	10.4 ± 0.6	10.6 ± 0.8		14.5 ± 0.8	16.5 ± 1.0		
Process criteria							
total number of solution steps	74.4 ± 8.9	69.1 ± 8.6	ns	148.6 ± 11.8	202.0 ± 22.3	.05	0.51
Including:							
– Providing steps	16.8 ± 1.3	18.1 ± 1.6		30.8 ± 2.2	40.8 ± 4.7		
– Adjustment steps	10.7 ± 1.4	9.9 ± 1.5	ns	22.2 ± 2.5	33.1 ± 4.8	.05	0.49
– Repeating steps	1.3 ± 0.4	1.9 ± 0.6		3.3 ± 0.5	4.9 ± 1.0		
– Rejecting steps	8.6 ± 1.3	9.8 ± 1.7		19.0 ± 2.5	30.4 ± 4.9		
– Positioning steps	22.6 ± 3.8	16.0 ± 3.4		39.7 ± 4.1	46.1 ± 7.1		
– Trying steps	14.4 ± 2.3	13.3 ± 1.9	ns	33.7 ± 2.8	46.8 ± 5.4	.05	0.53

One-sided testing because of directed hypothesis.
* Classification of effect size: small 0.20; medium 0.50; large 0.80; Bortz & Döring, 1995.

Discussion

In a questionnaire survey of more than 100 professional designers, more than half of them indicated they produced very effective rough sketches on paper, even during CAD. However, because of the large variety of tasks and CAD-systems involved, a detailed investigation was not possible. In the experiment described above, identical tasks had to be solved using the same software. The experimental situation allowed us to make distinctive observations and time analyses.

As expected, significant differences between the sketching and the non-sketching group only occurred with respect to the more complex problem presented. For the complex task, the total working time was significantly shorter for the sketching group despite additional time devoted to sketching, although the quality of the solution was not significantly better or worse in this group compared to the non-sketching group. Contrary to our expectations, a better quality solution was not achieved.

The lack of impact of sketching on the quality of the solution could be related to the possibility of testing the effectiveness of the elements used and their functions in TIM. Because the objectives had been clearly defined in the instructions, and because different solutions were generated, resulting from the different uses of the objects and the different subsequent steps, the main emphasis was placed on researching the process criteria and the impact on these of sketching. Operationalizing solution in terms of the number of objects needed reduces external validity. External validity was therefore only partially achieved in the present study for this variable as compared to practical CAD.

This study can be seen in the context of various investigations concerning the supporting effect of sketching and modelling. Within the boundaries of simulations carried out with samples of undergraduates, we were able to detect an increase in effectiveness by using relatively inexpensive means of support in the early phases of product-development processes. It may be possible to improve the quality of solutions significantly by sketching and modelling, without an increase in time required (Sachse, Hacker, Leinert & Riemer, 1999). The operationalization of the quality of the solutions was based on generally accepted quality standards. Experts determined the operationalization, using the criteria of function, production, assembly, arrangement and reliability. We evaluated the results by applying a process which assesses CAD results using value-analyses (Langner, 1991).

The supporting impact of sketching mainly concerns methods of approach. One explanation for the time saving can be found in the analysis of the process criteria. With sketching, the total number of steps is significantly reduced. This involves a smaller number of steps for chosing elements, testing them, adapting them to the necessary solution or rejecting them. While sketching, these processes, as analysis of the drawings and the statements confirmed, are anticipated in a rational way. Approximately 60% of the subjects (more than one answer was possible) reported that sketching was a considerable help in the analysis and formulation of a solution.

The results of this study confirm the findings of an earlier spot-check study which mainly sampled engineers. It shows that sketching, in addition to specific CAD- and VR-systems, leads to a decrease not only in the number of different kinds of steps needed, but also in the total number of steps needed. Free-hand sketching also has an impact on redundant, correcting and testing steps (Sachse, Leinert & Hacker, 2001) Thus, the supporting role of sketching in the design process can generally be regarded as independent of any factors specific to the software and therefore of CAD. The results obtained under controlled conditions confirm statements about the usefulness of free-hand sketching for CAD-work. The main practical implications can be found in two areas. First, enabling designers to make free-hand sketches with CAD is very helpful when handling complex problems. Second, free-hand sketching of technical objects should not be omitted in the education of young designers.

The study also identifies a need for further research. First it would be desirable to replicate the present findings with professional designers and tasks, and with requirements which are typical of product development. For financial reasons, it is virtually impossible to study practicing engineers or software developers. Both the experiment presented above and subsequent research using engineering students (Sachse, Leinert & Hacker, 2001) and mechanical engineering students (Schütze, Sachse & Römer, proposed manuscript) indicate an increase in effectiveness when additional forms of support are used. In particular the findings in the latter research can be applied more generally to realistic settings in the field of engineering.

Further explanations are needed as regards the characteristics which drawing functions included in the CAD-system have for the user if we are to understand the comfort and efficiency of free-hand sketching on paper. An example of a novel possibility of this kind for supporting design processes is Tangible CAD, based on an idea formulated by Sachse & Specker (1999a, 1999b). This idea has already been put into practice by Wirth & Zanini (1999). Tangible CAD should not, however, replace "classical" CAD but rather extend it.

Fundamentally, it remains to be explained whether, and if so, how external procedures such as sketching, noting, gesticulating or discussing during problem solving have a solution-generating role in terms of "external thinking", in addition to their effects in reducing memory load.

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