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External Thought—Does Sketching Assist Problem Analysis?

PIERRE SACHSE*, WINFRIED HACKER and SVEN LEINERT

Dresden University of Technology, Germany

SUMMARY

An experimental study ($n = 60$ students) tests the advantages of being allowed to sketch a representation of a mechanical system (involving components such as weights, ropes and pulleys) when one is to be subsequently asked questions about this system. In comparison to a control group who were not allowed to sketch the system, the main advantages of sketching were found to be a reduction in the perceived difficulty of the problems and an increase in the likelihood of correctly inferring relations between the components. These advantages came at no extra cost in terms of additional time being needed to analyse the situation or solve the problems. However, sketching conferred no advantage in terms of the correct recall of system components. Copyright © 2004 John Wiley & Sons, Ltd.

INTRODUCTION

Accurate problem representations have a considerable influence on the solution of technical problems in engineering design. If the representation of the problem is incorrect or incomplete, a correct solution cannot be expected (Roemer, Leinert, & Sachse, 2000; Roemer, Weißhahn, Hacker, & Pache, 2001).

Observing the way problems are solved in everyday life suggests that external procedures, such as writing or sketching, are applied in order to appropriately analyse the problem to be solved and as a basis for finding a solution. With the development of a solution the external problem representation is then modified (Sachse, Leinert, & Hacker, 2001a).

Overt external operations in the solution of problems are considered as external forms of thinking or simply as 'external thinking' (Rubinstein, 1984). These external operations produce external problem representations such as sketches, notes, or models made from materials that tend to be readily available at any time (for example pencil, paper, cardboard, paper clips, modelling clay, etc.). External processes in problem solving are even

*Correspondence to: P. Sachse, Department of Ergonomics, Otto-von-Guericke University Magdeburg, D-39106 Magdeburg, PF 4120, Germany. E-mail: Pierre.Sachse@Masch-Bau.Uni-Magdeburg.de

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implemented without the production of physical problem representations, for instance in speaking or gesticulating.

Such external problem solving processes have been described for both engineering design (Goel, 1995; Henderson, 1999; Purcell & Gero, 1998; Roemer et al., 2000; Sachse, 2002) and for scheduling (Pascha, Schöppe, & Hacker, 2001). A survey revealed, for example, that 55% of professionally experienced engineering designers often or always make sketches before starting Computer Assisted Design (CAD) work, and 36% of them use manual sketches in order to prepare further steps even during the CAD work (Roemer et al., 2001). Furthermore we could show in previous experimental studies that making manual paper-and-pencil sketching whilst doing CAD work corresponds with a significant decrease in the total number of working steps in design problem solving due to the decrease in repeating, correcting and testing operations (Sachse et al., 2001a; Sachse, Leinert, & Hacker, 2001b), a significantly improved quality of the solution (Sachse, Hacker, Leinert, & Riemer, 1999), a decreased—or at least not increased—total working time (Sachse, Leinert, & Hacker, 2001a), and a significantly lower rating of perceived task difficulty (Schuetze, Sachse, & Roemer, 2003).

However, it is less clear whether external thinking is helpful in all phases of design. Of particular interest is the extent to which the important initial phases of problem analysis and the development of a problem representation are supported. Moreover, there are as yet no empirically supported explanations for the improvement in problem solving by the external operations.

The most widespread explanation of these improvements is a reduction in memory load (Kavakli & Gero, 2001, 2002; Purcell & Gero, 1998). Alternative explanations to be found in the literature are the support of the problem solving process (Goerner, 1994; Tovey, Porter, & Newman, 2003), the identification of inconsistencies in initial solutions (Lippardt, 2000; S. Lim, PhD dissertation, 2002), and the reflection on the developed solutions (Wetzstein & Hacker, 2002). These attempts of an explanation are, however, mainly of a conjectural nature as some of them are based on case studies, where it is not always possible to identify causal relations.

Therefore, using problems from the field of mechanics, the present study examines whether sketching supports the problem analysis and thus the solution finding process and how this might be explained. For this purpose a problem type has been chosen whose solving mainly depends on the development and analysis of a correct problem representation and less on the detailed elaboration of the solution.

In order to facilitate the understanding of the questions presented below it is necessary first to briefly describe the tasks. Subjects were given written descriptions of two mechanical systems. They had to analyse them in order to answer questions on both the system components and on the relations between these components after the descriptions were withdrawn. One of the groups of subjects was requested to make sketches, the other was not allowed to do so.

QUESTIONS AND HYPOTHESES

We expect that in the sketching condition the percentage of correctly answered questions will be higher than in the non-sketching condition. This should be the case for both a less complex and a more complex problem and for both the reported system components and the reported relations between them. In addition sketching should increase the percentage of the correctly reported relations more than the percentage of correct system components (*hypothesis 1*).

The sketching and the non-sketching conditions should significantly differ only with regard to the percentage of correctly answered questions about the relations between the components. This should hold for both levels of task complexity (*hypothesis 2*).

We expect that the total working time required when sketching is requested will not significantly differ from the time when it is not allowed (*hypothesis 3*). This assumption results from the following reasoning: Manual sketching here is an uncomplicated kind of drawing that accompanies the mental text analysis and records external representations of the system so that a later reconstruction with repeated design steps will not be necessary. However, the sketches also may reveal possible errors in the representation of the system and thus may provoke a time-consuming correction of the design. This may contradict the assumption of no significant difference in required working time. In this case longer working time due to sketching activity will correspond with a higher solution quality (*hypothesis 4*).

We further expect a lower percentage of correctly answered questions concerning components of the system and the relations between them for a complex problem than for a less complex one in both the sketching and the non-sketching conditions (*hypothesis 5*).

Finally it is expected that in the sketching condition the perceived difficulty of problems is lower (*hypothesis 6*) and the perceived certainty concerning solutions is higher (*hypothesis 7*) than in the non-sketching condition.

The reasoning behind the assumed effect of sketching is as follows: Generally, problems of the given type are solved better with multiple, i.e. conceptual and visual-spatial representations and with switches between them than with unimodal representations (Krause, 2000). For sketching, the development of a visual-spatial representation—along with a conceptualization which is necessary in order to comprehend the verbal descriptions of the systems—is inevitable. In the case of more complex problems and the identification of relations, which unlike the system components are not initially provided, the support provided by sketching is far more important.

There are several arguments for the support provided by manual sketching:

— Mental activation is increased by manual sketching, as it is an additional, external sensorimotor process.
— Short-term memory is released, thus—following the trade-off approach—increasing mental capacity which becomes available for the analysis of the problem.
— An external, physical representation of the system is developed. This procedure, i.e. sketching the verbally presented system, requires on the one hand an elaborated type of information processing, and offers on the other an additional basis of recall: Participants may also remember their sketches when answering questions concerning the systems, and not only their mental representations.
— The sketch offers external feedback on the comprehension of the system.
— Translating a text into a sketch and not merely a mental image is assumed to require a comprehensive elaboration. Therefore we suppose that sketching leads to a more detailed analysis and thus to a more elaborated mental representation than is the case without sketching. A more detailed elaboration also means a more extensive encoding (compare the concept of the Levels of Processing; Craik & Lockhart, 1972).

Elaboration is assumed to be more comprehensive if the sketches concern the relations (for example the directions of movements of interdependent pulleys) than if they only concern system components (for example a fixed pulley). In this respect the relations are to profit more from sketching than the system components.

METHOD

Participants

The sample was composed of a total of 60 (49 female) students from different departments of the Dresden University of Technology. The average age of the participants was 22 years ($SD = 2.0$). Participants were randomly assigned to the experimental conditions. The working memory capacity of the participants was assessed with the Computing Span Test (Hacker & Sieler, 1997). A *t*-test for independent samples confirmed that the groups did not significantly differ with regard to their working memory capacity $t_{(58)} = 1.59$; $p = 0.12$ (two-tailed).

Materials and task

The written descriptions of two mechanical systems of differing complexity were presented to the participants. These tasks were adapted from Larkin and Simon (1987). The participants were instructed to analyse the problems in order to answer questions referring to the *system components* and the *relations within the system* without the possibility to use either the description or any sketches or notes. The box shows the description of the complex task.

The left end of a rope x is fastened- to a support.
It runs under a loose pulley A, over a fixed pulley B and under a loose pulley C.
The right end of the rope x is also fastened to the support.
Weight 1 hangs by means of a rope from the loose pulley A.
The fixed pulley D hangs by means of a rope from the loose pulley C.
Rope y runs over this fixed pulley D.
Weight 2 hangs from the left end of the rope y, weight 3 from the right.
The fixed pulley B is fastened to the support by means of a rope.
Pulley A is on the far left, pulley C on the far right.

Figure 1 illustrates the system described in the textbox; of course the figure was not presented to the subjects.

The participants answered in writing a set of 23 written questions for each system at the end of their analysis, and after the description and any sketches were removed. One part of the set of questions referred to the system components without considering their relations, while the other part referred to the relations between the system components. The questions about the system components (number and type of fixed or loose pulleys; number and type of ropes) did not need any inference, since participants read in the descriptions all the information necessary to answer this type of questions. Questions about relations, however, required additional inferences based on internal representations. Examples for both kinds of questions are presented in the text box:

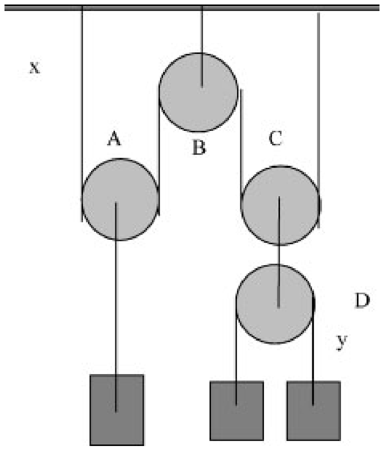

Figure 1. Example of a system

- System components:
  How many fixed pulleys come into action?
  How many ropes are needed for the system?
- Relations between the system components:
  Is the system balanced when all weights are one kilogram each?
  How many weights will fall down if rope y is cut?

Participants were free to determine the time they spent on the analysis and on answering the questions. These periods were recorded. The complexity of problems was varied. Complexity can be described as the number of elements of a system and of their relationships (Doerner, 1976). Therefore, we identified the number of the elements and of the relationships between them to assess the complexity of the problem (Larkin & Simon, 1987). Table 1 shows the results for the two problems.

Experimental design

We applied a design with the two independent variables *problem complexity* and *sketching possibility.* Problem complexity was a within-group variable, that is, each participant had to solve both problems. The sketching possibility was a between-group variable with the two levels: (1) request to sketch the components and relations described in the system (sketching condition) and (2) request not to sketch the components and relations described in the system (non-sketching condition) (see Table 2).

Table 1. Complexity of problems

Problems	1	2
Total number of system components to be identified	9	32
Total number of relations to be deduced	28	99

Table 2. Experimental design [2×2 mixed (between-group/within-group) design, $n = 60$]

Sketching possibility (between-group variable)	Problem complexity (within-group variable)	
	Low complexity (problem 1)	High complexity (problem 2)
Sketching condition	$n_1 = 30$	
Non-sketching condition	$n_2 = 30$	

In order to avoid sequence effects with the repeated variable (problem complexity) the sequence of the problems was balanced (Bortz, 1999). The subjects performed the experiment individually. The problems were presented in writing and the subjects answered the questions in writing.

Dependent variables

The dependent variables were the time for the analysis, time for answering the questions, number and percentage of correctly reported system components and relations, experienced difficulty, and perceived certainty regarding a correct solution. The operationalization of the dependent variables is shown in Table 3.

Absolute figures as well as percentages regarding the quality of the solutions are reported since the two problems of different complexity had different numbers of items. We further have to take into account that correct answers concerning system components can be given even if the relations were not identified or remembered, whilst correct answers concerning relations require the correct reproduction (or reconstruction) of the system components.

The data were subjected to a two-way analysis of variance with repeated measures, after the prerequisites were tested using the Greenhouse-Geisser-tests (Bortz, 1999).

RESULTS

The results regarding task *complexity*, here of secondary interest only, were in line with the expectations (see Table 4): Total time needed for the analysis was much higher for the

Table 3. Dependent variables and their operationalization

Dependent variables	Operationalization
Percentage of correct system components	Share of correctly identified system components
Percentage of correct relations	Share of correctly deduced relations
Time of analysis	Time spent to analyse the systems
Solving time	Time spent to answer the questions
Subjective difficulty of the problem	Assessed with bipolar rating scales (from 0 . . . *not difficult at all*, to 7 . . . *extremely difficult*)
Subjective certainty regarding correct solutions	Assessed with bipolar rating scales (with pole 0 . . . *not sure at all*, 7 . . . *completely sure*)

Table 4. Means (*M*) standard errors (*SE*) and effect sizes (*d*) for the problem analysis without and with sketching

Dependent variables	Analysis without sketching		Analysis with sketching		Differences and effect sizes concerning sketching influence			
	Low complexity (problem 1) *M* ± *SE*	High complexity (problem 2) *M* ± *SE*	Low complexity (problem 1) *M* ± *SE*	High complexity (problem 2) *M* ± *SE*	Low complexity (problem 1) Diff.	*d*	High complexity (problem 2) Diff.	*d*
Time of analysis (minutes)	1.9 ± 0.4	3.5 ± 0.3	1.9 ± 0.2	3.8 ± 0.3	0.0		0.3	
Solving time (minutes)	6.5 ± 0.4	7.7 ± 0.5	6.0 ± 0.4	7.7 ± 0.4	−0.5		0.0	
Perceived difficulty of the problem	2.2 ± 0.3	4.3 ± 0.3	1.2 ± 0.2	3.3 ± 0.3	−1.0*	0.60	−1.0*	0.57
Perceived certainty regarding correct solutions	4.5 ± 0.3	3.2 ± 0.3	5.3 ± 0.3	4.1 ± 0.3	0.8		0.9	
Total number of correct system components	7.6 ± 0.3	23.3 ± 1.2	8.4 ± 0.2	24.1 ± 1.2	0.8		0.8	
Total number of correct relations	25.4 ± 0.6	61.4 ± 3.9	26.3 ± 0.6	81.7 ± 3.3	0.9		20.3**	0.93
Percentage of correct system components	84.4 ± 2.9	72.9 ± 3.7	93.6 ± 2.0	75.3 ± 3.9	9.5		2.4	
Percentage of correct relations	90.8 ± 2.1	62.0 ± 3.9	94.1 ± 2.2	82.5 ± 3.3	3.3		20.5**	0.93

Note: $*p < 0.05$, $**p < 0.01$. For nonsignificant differences effect sizes are omitted.

complex task than for the simple one ($F(1.56) = 11.24$, $p = 0.01$). There was no significant difference in the time required to answer the questions ($F(1.56) = 2.32$, $p = 0.15$). The more complex task was experienced as more difficult ($F(1.57) = 16.76$, $p = 0.01$) and the estimated certainty to answer correctly was lower ($F(1.57) = 24.5$, $p = 0.01$). The percentage of correct answers with the complex problem was lower for both the system components and the relations ($F(1.57) = 24.56$, $p = 0.01$ and $F(1.57)$, $p = 0.01$, respectively). With the exception of the number of correct system components, these significant effects apply both to the sketching and non-sketching conditions. As expected, the results differ with respect to the two problems of different complexity. Hypotheses 2 and 5 are therefore supported.

Concerning the main question about the *influence of sketching* there were no differences with regard to the time required: Sketching neither led to a longer analysis time nor to a longer solving time ($F(1.56)$, $p = 0.30$ and $F(1.56)$, $p = 0.39$, respectively). As a consequence hypothesis 3 is supported. The percentage of correctly reported system components in the sketching condition was not significantly higher than in the non-sketching condition ($F(1.57) = 3.00$, $p = 0.15$). However, the percentage of correctly deduced relations was significantly higher in the sketching condition ($F(1.57) = 12.62$, $p = 0.01$). Hypothesis 1 is therefore only supported with regard to the relations. Concerning the reported relations there is also a significant interaction between sketching possibility and task complexity ($F(1.57)$, $p = 0.01$): Only for the complex problem was the share of correct relations significantly higher in the sketching condition as compared to the non-sketching condition: The influence of sketching on the number of correct relations for the complex problem was six times higher than for the less complex problem.

For both the sketching and non-sketching conditions and for both the complex and the less complex problems there were no significant correlations between the time of analysis and the time of answering and the percentage of correctly reported system components and deduced relations (maximum correlation of $r = 0.30 < r_{28;\ 0.05} = 0.37$). Hypothesis 4 is therefore not supported.

There are no significant differences between the sketching and non-sketching conditions with regard to the participants' subjective certainty regarding their solutions ($F(1.57)$, $p = 0.25$). As a consequence hypothesis 7 is not supported. However, the experienced difficulty was significantly lower in the sketching condition ($F(1.57$, $p = 0.05)$; there was no significant interaction between sketching possibility and problem complexity concerning difficulty. Hypothesis 6 is supported.

DISCUSSION

This study was carried out as a consequence of the results of a survey study with professionally experienced designers, in which more than half of them reported making use of sketches before and during CAD work. Experimental studies revealed that sketching, as well as impromptu modelling, lead to improvements in design effectiveness, and to a reduction in the total number of steps needed in the engineering design process. This reduction can be explained by the significantly lower numbers of repeating, correcting and testing steps (Sachse, 2002; Sachse et al., 2001b).

In the literature there is evidence that sketching relieves memory load and there are further indications that sketching might also support thought processes. This is the subject of this study, which focuses on the initial phase of problem solving, especially on problem analysis.

The findings of this study can be summarized as follows: Sketching neither increases the time necessary for problem analysis nor the time required to answer questions. No significant differences regarding the percentage of correctly reported system components could be found between the sketching and non-sketching groups. However, there was a significantly higher percentage of correctly inferred relations between components of the system in the sketching condition. This especially applies to the complex problem. There was an interaction between problem complexity and sketching possibility. In addition, the perceived problem difficulty was lower in the sketching condition.

Do these results provide evidence that sketching supports not only memory but actually also thinking? In a first step, we will summarize what *cannot explain* the sketching effect.

Sketching only took place during the analysis of the problem and the sketch was only present during this period of time. This means that the sketch could not offer external memory support while answering the questions. In addition, sketching did not significantly prolong the period of analysis. Therefore the sketching effect cannot be explained by a longer possibility to encode the information in memory.

Sketching did not enhance the percentage of correct system *components*, which only had to be recalled when responding but had not to be inferred. This finding cannot be the result of a ceiling effect as there were further possibilities of improvement. Therefore, other possible explanations for the missing effect of sketching on the reported number of correct system components must be found. One possibility is that since the system *components* were already conceptually presented in the problem description, they required in order to be sketched no inferences that might have improved their encoding in memory as an elaboration. If this assumption is true there should have been in contrast a sketching effect concerning the *relations*, which first had to be inferred from the description before they could be sketched. And only in this case sketching significantly improved the share of correctly reported relations.

In looking for an explanation it could be the case that the perception of a sketch leads to a visual-spatial encoding of the relations in addition to the conceptual encoding required to understand the verbal system descriptions. Furthermore, there is a tactile-kinaesthetic feedback of the sensorimotor sketching process as an additional kind of encoding. However, this multiple encoding cannot explain completely the improvement of the inferred relations with sketching, since the system components were to be sketched, too. Thus they might also be multiply encoded and consequently recalled better after sketching. However, this was not the case.

Which possible explanations remain? First of all, during the problem analysis sketching relieves short-term remembering. In the sense of the remembering-processing trade-off in working memory sketching releases mental capacity in favour of the inference of the relations.

In addition to this explanation in terms of mental capacity a further explanation may exist: Inference of the relations of the systems (e.g. direction of movements) may profit more than the recall of already given components (e.g. pulleys) from the cognitive effort required to recode the verbal-conceptual descriptions of the systems into the graphic-pictorial ones, i.e. the sketches. This seems a plausible explanation since it is well-known that changes in the mode of information representations stimulate reclassifications and inferences (Bartl & Doerner, 1998; Krause, 2000). Moreover, the requirement to develop an external pictorial representation could highlight missing relations or contradictions. For example, it may become immediately visible that the left end of the rope is fastened to a support instead of a pulley.

Finally, sketching transfers a mental problem solution into a physical object, which the problem-solver may process as the subject of a critical examination, i.e. of his or her meta-cognitive reflection. We propose that the reflective analysis of a problem benefits from its external representation, for example a sketch, in comparison to a mental representation which is not externally fixed and therefore fleeting.

The explanations discussed imply that sketching is not a mere fixation of finished solutions but an external part of the mental process itself.

The analysis of the contents of the sketches will be the next step in testing the explanations of the impact of sketching presented above.

A possible extension of the results to other psychomotor processes, like writing or impromptu modelling, could have considerable theoretical and practical consequences. In theories of thinking the role of speaking and of other psychomotor processes is disputed (see Anderson, 1995; versus Bartl & Doerner, 1998; Klix, 1992; Krause, 2000). Regarding everyday learning and work processes, this line of research may provide an important contribution to a more systematic application of external psychomotor components to effectively support thinking.

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AUTHORS' NOTE

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