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**MAX-PLANCK-INSTITUT FÜR PSYCHOLOGISCHE FORSCHUNG**

LEOPOLDSTRASSE 24 80802 MÜNCHEN / POSTFACH 440109 80750 MÜNCHEN

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# 13

# A microgenetic longitudinal study on the acquisition of word problem solving skills

*E. Stern*

## Introduction

Arithmetic word problems that require the same mathematical equation can vary considerably in difficulty. Some word problem types dealing with the exchange (e.g., 'In the beginning, John owned five marbles. Then Peter gave him two other marbles. How many marbles does John have now?') or the combination (e.g., 'Peter has five marbles. John has three marbles. How many marbles do John and Peter have altogether?') of sets can be solved by kindergarten children who have not had any mathematics instruction. However, problems dealing with the comparison of sets are difficult even for third graders, although the arithmetic operations necessary to solve the problems have been taught at the beginning of elementary school. Currently, we now know a good deal about the process of solving word problems and reasons for the difference in difficulty between word problem types (Cummins, Kintsch, Reusser & Weimer, 1988; Kintsch & Greeno, 1985; Riley & Greeno, 1988; Stern, 1992). However, similar to other domains of problem solving, little is known about the *acquisition process* of the competencies necessary for understanding and solving such problems. For example, what changes in knowledge representation, or what instructional input is necessary to enable children to understand and solve particular word problems?

Studying conditions of knowledge acquisition is difficult for several reasons. First, as it is only possible to measure performance, but not knowledge representation itself, one can only infer necessary abilities and knowledge representation from performance. Thus, if one wants to learn about the processes of knowledge acquisition and restructuring that enable subjects to solve certain types of problems, one has to develop tasks that demand abilities that themselves are initial stages of the competence necessary to solve the task one is interested in. Second, to study processes of knowledge acquisition it is necessary to investigate the same person repeatedly with only short intervals between measurement points. This 'Microgenetic longitudinal method' requires a considerable amount of time and effort (Siegler & Jenkins, 1989).

This chapter focuses on the question as to what competencies have to be acquired in order to solve problems dealing with the *comparison of sets*. Table 1 depicts the different types of compare problems.

**Table 1:** *Types of compare problems* (CP)

| | |
|---|---|
| **Unknown difference set** | |
| CP1 | Mary has 5 marbles. John has 8 marbles. How many marbles does John have more than Mary? |
| CP2 | Mary has 6 marbles. John has 2 marbles. How many marbles does John have less than Mary? |
| **Unknown compare set** | |
| *Large set unknown* | |
| CP3 | Mary has 3 marbles. John has 4 marbles more than Mary. How many marbles does John have? |
| *Small set unknown* | |
| CP4 | Mary has 5 marbles. John has 3 marbles less than Mary. How many marbles does John have? |
| **Unknown reference set** | |
| *Small set unknown* | |
| CP5 | Mary has 9 marbles. She has 4 marbles more than John. How many marbles does John have? |
| *Large set unknown* | |
| CP6 | Mary has 4 marbles. She has 3 marbles less than John. How many marbles does John have? |
| **Complex problems** | |
| CPC1 | Peter has 5 marbles. John has 2 marbles more than Peter has. How many marbles do John and Peter have altogether? |
| CPC2 | Peter has 5 balls. He has 3 balls less than Susan has. John has 4 balls less than Susan has. How many balls does John have?' |
| CPC3 | Mary has 4 marbles. She has 3 marbles less than John. How many marbles does John and Mary have altogether? |

Compare problems with an *unknown reference* set present special difficulties (Lewis & Mayer, 1987; Stern, 1993a; Verschaffel, De Corte & Pauwels, 1992). In addition to the usual six one-step compare problems depicted in Table 1, Stern (1993b) developed *more-step* problems which demand the inference of special information, such as 'Peter has 5 marbles. John has two marbles more than Peter. How many marbles do John and Peter have altogether?'. These problems are solved correctly by about 25% of second graders (Stern, 1993b). However, even solution rates such as these are remarkable because in elementary school complex word problems are very rarely presented to the children. The children therefore have to develop their own solution strategies based on their mathematical understanding. One way to study the process of the acquisition of the abilities necessary for solving word problems is to offer a training program to the children, and then to investigate how children use the knowledge they have been offered. In the research we are report here, the microgenetic longitudinal method was combined with a training program to find out how children acquire the knowledge necessary to solve compare problems with an unknown reference set and complex more-step compare problems that demand the inference of information.

Several simulation studies on understanding and solving arithmetic word problems have suggested what sorts of knowledge have to be trained to promote word problem solving competencies.

## Competencies necessary for understanding and solving word problems

Understanding and solving arithmetic word problems requires text comprehension as well as mathematical understanding. In the last five years, two different research approaches to young children's word problem solving have been developed: The logico-mathematical approach from Riley and Greeno (1988) and the text-comprehension approach from Cummins, Kintsch, Reusser and Weimer (1988).

According to the logico-mathematical approach, some word problems require the representation of conceptual mathematical knowledge such as the part-whole schema and are therefore more difficult than others that only require counting procedures and can be solved by direct modelling. The part-whole schema provides flexibility in building mathematical equations and, therefore, if a subject has represented this knowledge, the solution process consists only of accessing an equation appropriate for the word problem. According to the logico-mathematical model, compare problems with unknown difference set (CP1, CP2 in Table 1) do not require part-whole knowledge but rather can be solved by match-separate-strategy. However, several transformations are necessary to solve a problem with an unknown reference set (CP5, CP6 in Table 1), (Lewis & Mayer, 1987; Stern, 1993a; Verschaffel, De Corte & Pauwels, 1992). These transformations require access to the quantitative compare schema. This schema is based on the part-whole schema and allows one to deal with the sets involved in quantitative comparison (difference set, compare set, reference set) in a flexible way. Depending on whether the compare set is the small set and the reference set is the large set or the other way around, one can build several equations. The logico-mathematical approaches assume that with development children build different mathematical models for different kinds of word problems.

With respect to mathematical models, a distinction is made between action-based models and part-whole models. In action-based models, addition means getting more and subtraction means something is taken away. Word problems that describe the exchange of sets can be mapped on such action-based models. Part-whole models are based on the arithmetic part-whole schema: addition and subtraction are understood as complementary ways of describing situations. In action-based models, a dynamic view of addition and subtraction is emphasized. The equation 3+5=8 is understood as 'if one puts together three elements and five elements, one has eight elements altogether'. In part-whole models, the equation 3+5=8 is understood as 'three plus five is another name for eight'.

Being in possession of the part-whole schema enables students to understand and solve problems such as problem CPC1 in Table 1. Only if one can access a quantitative compare schema can one know that one has to find out how many marbles John has by adding the difference set and Peter's numbers of marbles.

According to the text-comprehension approach, the content of word problems is what makes some problems difficult, either because the language is not understood or because the situation described in the story is unfamiliar. Thus text-comprehension deficits prevent subjects from making contact with the adequate mathematical knowledge. The assumptions made by the text-comprehension approach are clearly supported by empirical results, especially as far as problems dealing with the comparison of sets are concerned. Facilitating effects from changing the language and the story context have been shown (Cummins, 1991; Davis-Dorsey, Ross & Morrison, 1991; Hudson, 1983; Stern & Lehrndorfer, 1992). Problems dealing with the comparison of sets become easier if they deal with situations that refer to the goal of making two sets equivalent. A problem that begins with 'John has 5 marbles. Peter has 3 marbles.' is much easier when it finishes with an equalize question such as 'How many marbles must Peter get in order to have the same amount of marbles as John?' than when it ends with a compare question such as 'How many marbles less than John does Peter have?' (Riley, Greeno & Heller, 1983). Hudson (1983) found that most of the kindergarten children solved the problem 'There are five birds and three worms. How many birds won't get a worm?' while only very few children could solve the same problem if it ended with the question 'How many more birds than worms are there?'

Although undoubtedly both textual and mathematical understanding are important for solving word problems, one can ask the question of how to improve word problem solving competence. According to the logico-mathematical approach, the acquisition of the part-whole schema is crucial for improving performance in word problem solving, because it allows the transfer of textual information to a mathematical equation. In order to improve competence in word problem solving therefore, one should train the understanding of part-whole relations. Resnick and Greeno (1990) have developed several suggestions as to how to do this. According to the text-comprehension approach, a word problem can be solved when one is able to understand what textual information has to be used for building a quantitative problem model.

In the present study, the process of knowledge acquisition was investigated by combining two methods: the training method and the microgenetic longitudinal method. Children were trained either in mathematical understanding, in situational understanding or received no special training. All children had to solve compare problems once a week to investigate progress in performance. Two main questions addressed in this study were:

1. How do the different training programs affect different types of word problems? It is expected that situational training is superior for compare problems with an unknown difference set and unknown compare set while performance on unknown reference set problems and complex compare problems that demand flexibility in mathematical knowledge can only be improved by training the understanding of part-whole relations.
2. A second question regards the elucidation of the processes of acquiring competencies, in particular the order of acquisition of different aspects of competencies and whether there is a delay between knowledge acquisition and being able to use this knowledge in problem solving. It is unlikely that acquired knowledge such as the part-whole schema will be used immediately. Rather, in line with Siegler and Jenkins (1989), we expected a delay before acquired knowledge could be used for solving a problem.

## Method

### *Subjects*

Thirty-six second graders participated in the study. The subjects were selected from a total of 56 children in different Munich after-school centres who had been given a pretest on solving compare problems. The 36 children who were selected for the training had to fulfil two criteria: first, they had to have solved correctly at least 75% of the reworded compare problems such as those presented by Hudson (1983) and Stern (1994) (e.g., 'There are five birds and three worms. How many birds won't get a worm?') and equalize problems (e.g., 'John has five marbles. Peter has three marbles. How many marbles must Peter get in order to have the same amount of marbles as John'); and second, they had to have failed at least 80% of the compare problems with an unknown reference set and more-step compare problems such as the problems CPC1 in Table 1. Thus, the students who participated in the microgenetic longitudinal study could solve problems that dealt with the goal of making two sets equal, but they still had to learn to solve problems that required rather abstract knowledge about the comparison of sets. In addition, subjects who were equal in their performance-pattern on compare problems were assigned to each of the two training groups or the control group by triples. The study was initiated in September 1991 (beginning of the school year) and concluded in July 1992. Within the training period, five children dropped out because they lost interest or because they left the after-school centre.

### *Procedure*

The children were tested and trained individually in an after-school centre once or twice a week by a research assistant. The testing schedule is depicted in Table 2. Each session took 30 - 60 minutes. In the first four sessions children were tested for intelligence with a German version of a culture fair intelligence test, (CFT 1, Weiß & Osterland, 1979), arithmetic abilities (Scholastik-test, Stern, 1993b) and were given word problems.

The word problem pretest was as follows: The children were presented with a test containing 35 word problems in two sessions. Given that we were especially interested in compare problems, each of the six types (unknown difference set, unknown compare set, unknown reference set, each one with either using 'more' and one using 'less') was presented three times, once in the two-person form ('John has three marbles. Peter has five marbles. How many marbles does Peter have more than John?') and once in the two-object form (There are three cows and five pigs. How many more pigs than cows are there?') and once in the person-object form such as 'There are six apples and four children. How many more apples than children are there?'. Further, twelve other one-step problems were presented: two equalize problems and two reworded compare problems (Hudson, 1983), and the eight change and combine problems mentioned in Riley, Greeno and Heller (1983). In addition to the one-step word problems, five more-step word problems were designed, such as those presented in Table 1. The children had to solve all problems by writing down the mathematical equation used and by orally giving the answer in a sentence.

### *Training conditions*

The children were assigned to the three training conditions by matching 'triplets' as described earlier. One member of each 'triplet' was assigned to each training condition. In sessions 4 - 7, all children received training, but did not receive compare problems. In the training conditions, children were presented problems to solve. If a child did not perform correctly, the experimenter explained the correct answer in a predetermined way. Only after a child had performed correctly, was the next problem presented. The time per training differed therefore according to the child.

#### *Mathematical training*

The goal of the training program was to enable the children to understand the complementary relation between addition and subtraction. The children were shown that one number, for example seven, is composed of different sums, such as 2+5 or 1+6 and were asked to find out similar addition equations for different numbers. Parallel training sessions were practised with subtraction equations. Here children were requested to write down all subtraction equations that result in, for example, 7, given that the first number was not larger than 20.

The children were also trained in understanding that two equations can be equivalent such as 4+2=9-3 and had to solve problems such as ?+3=8-2. In addition, they were asked to make several mathematical equations out of number triples, such as 6, 2, 4 (2+4=6, 4+2=6, 6-2=4, 6-4=2).

#### *Situational Training*

The goal of this training program was to make the children aware of the relation between formulations such as 'n less than' or 'n more than' and familiar situations using results from rewording studies (Hudson, 1983). Children were presented with

***Table 2:*** *Time schedule of the test application and the training*

| Session | |
|---|---|
| 1-2 | Word problem solving |
| 3 | Non-verbal Intelligence |
| 4 | Arithmetic Abilities |
| 5-8 | Training Programs<br>Mathematical Situational Reasoning |
| 9-10 | Training-Test, First Posttest |
| 11-16 | Mixed Training Programs<br>Mathematical Situational Reasoning |
| 17 | Second Posttest |

problems such as 'five birds are hungry. They find three worms.' and were given two pairs of questions:

a) How many birds won't get a worm?
   How many more birds than worms are there?
b) How many worms are missing?
   How many fewer worms than birds are there?

In the first training session, children were requested to answer each question and their attention was called to the fact that the same information can be asked by using quite different verbal expressions. This allows the children to understand that the question 'how many more/less objects are in Set A than in Set B' is equivalent to the question 'how many objects are needed to make set A and set B equivalent?'. In later training sessions children were given problems with several different questions and their task was to find out which questions asked for the same information, despite differences in verbal formulation.

*Control Condition*

Under the control condition the children received reasoning training tasks developed by Klauer (1989). Children had to practice on different induction problems similar to Culture Fair Intelligence Test problems.

### *Test Application*

The following tests were presented to all children.

1. Training test
   The items were similar to those presented in the situational and mathematical

training sessions. The purpose of this test was to find out whether children's performance in the trained components had improved.

2. First Posttest
   Twelve one-step compare problems (two of each type in Table 1, one two-person problem and one two-object problem) and five complex compare problems were presented in a procedure similar to the pretest.
3. Second Posttest
   The follow-up test was the same as the first posttest.

## Results

Complete data were available from ten children of the control condition, eleven children of the situational training condition, and ten children who had been administered the mathematical training. However, as the performance of the drop-outs varied, we only analyzed the data of nine children of each group because, otherwise, the groups would have differed in the performance of the pretest. The three groups were comparable with respect to General Intelligence (the mean IQs were: Control Group: 101.3; Situational Group: 99.5; Mathematical Group: 102.4), performance in the Arithmetic Abilities test (the mean solution rates were: Control Group: .53; Situational Group: .59; Mathematical Group: .47), and performance in word problem solving (the mean solution rates were: Control Group: .48; Situational Group: .42; Mathematical Group: .45).

The following questions were addressed:

*Did subject's performance in the problems they had been trained in improve?*
Figure 1 depicts the means of the 'Training test'. Overall, children improved their performance in the tasks specific to the training they had received. A detailed individual analysis showed that this overall result represented improvement by each child on the trained problems. A one-way analysis revealed that those subjects who had received the situational training performed better on problems demanding the reformulation of compare problems than the other two groups, $F\ (2,24) = 2.5, p<.10$). Another one-way analysis revealed that the subjects who had received the mathematical training performed better in the numerical tasks than the subjects who had been administered the situational training or the control training $F\ (2,24) = 15.8$, $p<.01$).

*Was the immediate training successful for solving word problems?*
Figure 2 depicts the means of word problems solved in the first posttest. The results show that after four training sessions, performance was somewhat better for the subjects of the training conditions than for subjects of the control condition, $F\ (2,24) = 2.55, p<.10$). Separate analyses for each problem type indicated that subjects of the situational group performed better on problems with unknown difference set ($F\ (2,24) = 5.28, p<.01$) and unknown compare set ($F\ (2,24) = 4.8, p<.05$) than did subjects of the other two groups. For the other problem types no significant difference was found on the $p<.05$ level.

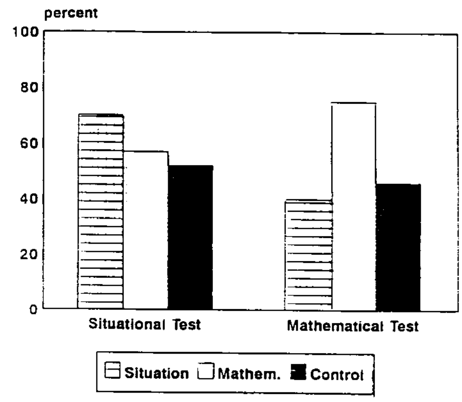


**Figure 1:** *Mean percentage of problems solved in both Training tests, depicted separately for each training condition (Situational, Mathematical, Control condition)*

At this time of measurement, the part-whole training did not have an effect on the solution of compare problems, whereas situational training was helpful at least for easier compare problems. This indicates that some of the difficulties with compare problems are due to a lack of text comprehension: the formulation 'more/less than' does indeed prevent the children from constructing an adequate situational model and thus does not allow them to access the adequate mathematical knowledge. However, there was no effect of situational training on problems with an unknown reference set and complex compare problems, indicating that solving these problems requires more than relating the problems to a familiar situation.

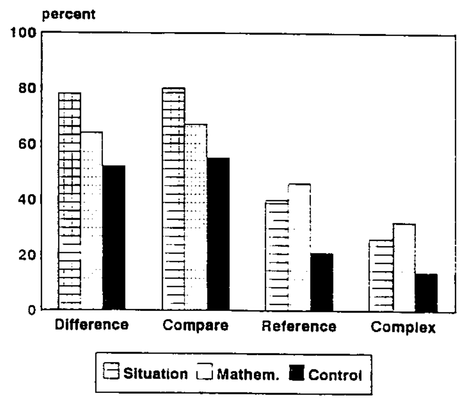


**Figure 2:** *Mean percentage of compare problems solved in the first posttest, separately for each training condition (Situational, Mathematical, Control condition) and each problem type (problems with unknown difference set, compare set, reference set, and complex compare problems).*

The results from the mathematical training group show that although training helped children to become more flexible in understanding and handling mathematical equations, which means that they could represent the part-whole schema, this did not help them to solve compare problems. This suggests that part-whole knowledge - assuming that it is helpful at all - is not used spontaneously for solving compare problems. This result is in line with several results from other transfer studies: Knowledge acquired in one situation is only used to solve a problem in another situation if subjects are given special hints to apply this knowledge in the new situation (Salomon & Globerson, 1987).

*Was the mixed training successful for solving word problems?*

As mentioned before, in the mixed training sessions children had to solve compare problems and, in the case of an incorrect response, were given another chance in addition to the specific training (situational, mathematical, control). Figure 3 depicts the mean solution rates aggregated over all types of word problems for the sessions 11 - 16.

Initially, performance in the control group and in the situational group increased while only in the mathematical condition could a constant increase over all training sessions be found. This indicates that many children in the mathematical condition started to use their part-whole knowledge to solve unknown reference set problems and complex compare problems in the later training sessions.

In Figure 4 the mean solution rates found in the second posttest for each compare problem type are depicted. Subjects of the training conditions performed better than subjects of the control conditions, $F\ (2,24) = 4.28$, $p<.05$. Similar to the results from the immediate posttest, performance in problems with unknown difference set ($F\ (2,24) = 8.0$, $p<.01$) and unknown compare set ($F\ (2.24) = 8.0$, $p<.01$) only improved under the situational training condition.

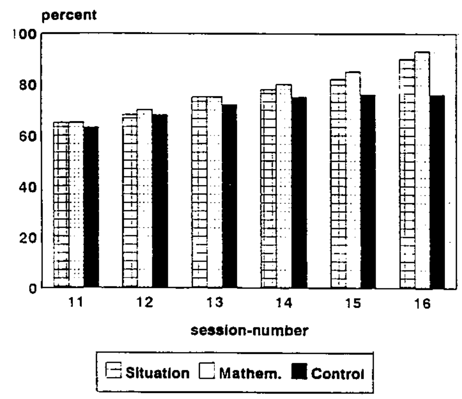


**Figure 3:** *Mean percentage of compare problems solved in the mixed-training sessions, depicted separately for each training condition (Situational, Mathematical, Control condition)*

However, in contrast to the results of the first posttest, one-way analysis based on the results of the second posttest indicated that the subjects of the mathematical training conditions performed better on complex problems ($F$ (2,24) = 7.5, $p$<.01) and problems with unknown reference set ($F$ (2,24) = 6.0, $p$<.01).

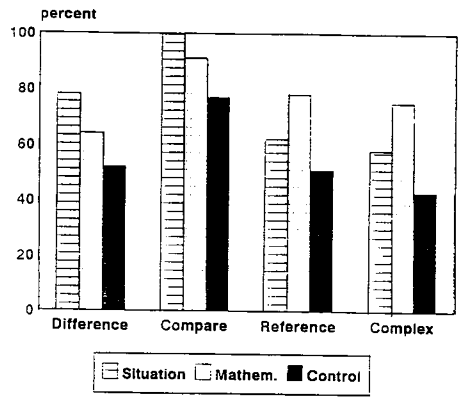


**Figure 4:** *Mean percentage of compare problems solved in the second posttest, depicted separately for each training condition (Situational, Mathematical, Control condition) and each problem type (problems with unknown difference set, compare set, reference set, and complex compare problems)*

## Discussion

The results from the control group show that children improve their performance in all types of word problems when they receive feedback and have a chance to solve problems twice even without a specific training. However, the children who received specific training programs improved their performance beyond this *spontaneous* raise in performance. The data indicate that there is an interaction between problem type and training condition. Whereas performance in solving easier problems (unknown compare set problems and unknown difference set problems) improved in the situational condition, there was no effect on performance when more difficult problems (unknown reference set problems and complex compare problems) were used. The effect of the mathematical training condition was just the reverse: at the end of the training session, performance increased considerably for the more difficult problems but not for easier problems. Taken together, these results suggest that poor performers in particular profit from situational training, whereas good performers profit from mathematical training.

However, the results of the immediate posttest in the mathematical condition also indicated that there was no initial spontaneous transfer from the part-whole knowledge, even at the individual level: none of the children spontaneously transferred the part-whole knowledge acquired in the first four training sessions to word problem solutions. Rather, there was a gradual increase of the mean solution rates only in the mixed training sessions. Therefore, children learned to use their mathematical knowledge when solving problems that demand the representation of the mathematical compare schema only after practice and with presentation of the part-whole training and compare problems in the same session.

In the introduction the logico-mathematical and the text-processing approach of modelling word problem solving were contrasted. It was stated that the logico-mathematical models explain children's difficulties in understanding and solving compare problems by a lack of mathematical understanding, while in text-processing models it is assumed that the difficulties can be explained by a lack of matching textual information to mathematical models. Our results recommend that both models are true in some respect. An elaborated understanding of addition and subtraction, that means part-whole knowledge, seems to be a prerequisite for solving more difficult compare problems. However, simple compare problems can also be solved by accessing an action based model of addition and subtraction, if this is suggested by the language used in the problems. Thus, logico-mathematical models and text-processing models do explain two different, but equally valid reasons for failing to solve a word problem.

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