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Journal
Proceedings of the Annual Meeting of the Cognitive Science Society, 20(0)

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Publication Date
1998

Peer reviewed

Steps Towards the Acquisition of Expertise: Shifting the Focus from Quantitative to Qualitative Problem Representations During Collaborative Problem Solving

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Abstract

Three important findings of research on expertise in formal sciences such as physics are that novices and experts differ with respect to (1) how they structure their domain knowledge, (2) how they mentally represent problems and (3) how they approach problems. Though first attempts have been made to account for the acquisition of knowledge structures as possessed by experts, the reconstruction of the involved learning mechanisms in a psychologically plausible and instructionally fruitful way still remains a challenge. In an experimental study, we investigated how tenth graders acquire and successively relate qualitative and quantitative problem representations in classical mechanics. Initially, subjects were taught either qualitative or quantitative aspects of classical mechanics. Afterwards, two subjects, who were taught differently, collaborated on problems which were beyond the competence of each of them separately. Before and after the collaboration subjects had to work on multi-component tests. In addition, protocols were taken of the subjects' verbal exchange of information during collaborative problem solving. An analysis of variance of the multi-component tests revealed that the subjects successfully learned to interrelate qualitative and quantitative problem representations. A protocol analysis further indicated that subjects gradually shifted their focus from quantitative problem representations to qualitative problem representations during collaborative problem solving.

Introduction

Within the last 20 years, cognitive science research on expertise in formal sciences such as physics has revealed various differences between novices and experts (for overviews see Chi, Glaser & Rees, 1982; VanLehn, 1996). Three important findings are that novices and experts differ with respect to (1) how they structure their domain knowledge, (2) how they mentally represent problems and (3) how they approach problems.

While novices frequently seem to possess knowledge structures in which different aspects of an application domain such as empirically observable aspects and theoretical aspects remain separated, the knowledge of experts seems to be structured in such a way that different aspects of an application domain are tightly interrelated (e.g., Chi, Feltovich & Glaser, 1981). Furthermore, while novices predominantly represent posed problems on the basis of empirically observable aspects, experts primarily represent problems on the basis of theoretical aspects such as qualitative-conceptual and quantitative-numerical aspects.

The mentioned differences in knowledge structure and problem representation severely affect how novices and experts approach standard textbook physics problems (e.g., Chi, Feltovich & Glaser, 1981; Larkin, 1983). To solve a posed problem, in a first step novices frequently construct a problem representation that pictures the different objects named in the problem description. Such a problem representation, however, can hardly be taken advantage of when the appropriate domain principles and equations need to be selected for application.

Therefore, in a second step novices commonly attempt to construct a quantitative-numerical problem representation by algebraically combining equations. Thereby they typically work backwards from a variable whose value has to be determined (e.g., Larkin, McDermott, Simon & Simon, 1980). Yet, in many cases novices get lost in a muddle of equations with no means at hand to apply them successfully and efficiently.

Experts, in contrast, initially make use of their theoretical domain knowledge to approach a posed problem qualitatively and to construct a qualitative-conceptual problem representation. Afterwards, such a representation is taken advantage of to constrain and to direct the construction of an appropriate quantitative-numerical representation.

As a consequence of these findings, artificial intelligence research, educational research as well as psychological research have directed increasingly more attention towards the construction of qualitative problem representations and how they can be used to construct appropriate quantitative problem representations.

Though first attempts have been made to account for the acquisition of knowledge structures as possessed by experts (e.g., Elio & Scharf, 1990), the reconstruction of the involved learning mechanisms in a psychologically plausible and instructionally fruitful way still remains a challenge. In an experimental study, we investigated how tenth graders acquire, extend and successively relate qualitative and quantitative problem representations in classical mechanics during collaborative problem solving.

The results of the study provide evidence that the subjects did not only learn to successfully interrelate qualitative and quantitative problem representations but also that the subjects gradually shifted their focus from quantitative problem representations to qualitative problem representations during collaborative problem solving. These findings can be interpreted as first steps in the acquisition of knowledge structures as they are possessed by experts.

The rest of the paper is organized as follows. In the next section, the distinction between qualitative-conceptual and quantitative-numerical problem representations is set forth. The design of the empirical study, the materials used, the procedure applied and the results observed are reported next. A discussion concludes the paper.

Qualitative and Quantitative Problem Representations in Classical Mechanics

The investigated application domain is made up of standard textbook physics problems which involve one-dimensional motion with constant acceleration. The knowledge under scrutiny is knowledge about qualitative and quantitative aspects of various concepts in dynamics (e.g., gravitational force, normal force, and friction force) and kinematics (e.g., time, position, displacement, velocity, and acceleration).

Knowledge about qualitative aspects encodes information such as the conditions under which concepts can legitimately be applied, the attributes possessed by concepts and the values concept attributes might have. It might specify, for example, that there is a kinetic friction force on an object, whenever there is a normal force on the object and the object is moving on a surface which is not frictionless.

Knowledge about quantitative aspects encodes information about interaction and motion laws. It relies on mathematical formalisms to describe definitions of and functional relationships between concepts by means of algebraic and vector-algebraic equations. It might specify, for instance, that the magnitude of the kinetic friction force F_f on an object equals the magnitude of the normal force F_n on the same object times the coefficient of friction f: $F_f = F_n \times f$.

As de Kleer (1975) points out, knowledge about qualitative and quantitative aspects cannot be separated at a clear-cut boundary. Rather, this distinction refers to the ends of a continuum with a considerable body of knowledge between them (e.g., Ploetzner, Spada, Stumpf & Opwis, 1990; White & Frederiksen, 1990).

We conceptualize qualitative and quantitative problem representations as complementary representations based on knowledge about qualitative and quantitative aspects, respectively (see Ploetzner, 1995). Qualitative problem representations include information about essential problem features to be taken into account and important distinctions to be drawn. While quantitative problem representations help to resolve ambiguities frequently inherently involved in qualitative problem representations, qualitative problem representations are a prerequisite for the appropriate construction and use of quantitative problem representations.

Method

Design

Two experimental groups and one control group were formed. 24 subjects from two different schools were equally distributed among the three groups. All subjects had to work on a pretest, an intermediate test and a posttest. Between the pretest and the intermediate test, the subjects out of the experimental groups worked on two different instructional units. While the subjects out of the first experimental group worked on an instructional unit on qualitative aspects of classical mechanics, the subjects out of the second experimental group worked on an instructional unit on quantitative aspects of classical mechanics.

Between the intermediate test and the posttest, dyads were formed with subjects who had received different instructional units. They worked collaboratively on four classical mechanics problems which were beyond the competence of each of them individually and which demanded the interrelation of qualitative and quantitative problem representations. The subjects out of the control group did not receive any treatment between the different tests.

Materials

Instructional Units Two instructional units on classical mechanics were constructed. One unit described qualitative aspects of classical mechanics and one unit described quantitative aspects of classical mechanics. Both units comprised sections on (a) coordinate systems and vectors, (b) resolution and addition of vectors, (c) velocity and acceleration and (d) forces. The qualitative and quantitative aspects of the addressed concepts were presented by means of concept maps (e.g., Novak, 1990). One or more concept maps were followed by several examples and exercises. The solutions to the exercises were also presented. Each instructional unit comprised about 90 pages.

Problems Four different classical mechanics problems for collaborative problem solving were set up. They are shown in Table 1. Each problem asks for a precise quantitative solution. However, in order to necessitate collaboration during problem solving, the problems were designed in such a way

Table 1: Problems for collaborative problem solving

Problem 1: A coin of mass $m = 0.03$ kg is tossed straight up into the air with the velocity $v = 7$ m/s. After which distance r is the coin's velocity reduced to $v = 3$ m/s?

Problem 2: A block of mass $m = 15$ kg starts from rest (initial velocity $v = 0$ m/s) down a frictionless ($f = 0$) plane inclined at an angle $\alpha = 30^0$ with the horizontal. What is the block's velocity v after the time $t = 2$ s?

Problem 3: What is the minimum stopping distance for a car of mass $m = 820$ kg travelling along a flat horizontal road with the velocity $v = 12$ m/s, if the coefficient of friction f between tires and road equals 0.8?

Problem 4: A block of mass $m = 10$ kg is projected up an inclined plane with the velocity $v = 5$ m/s. The plane is inclined at an angle $\alpha = 15^0$. Which distance r up the plane does the block go, if the coefficient of friction f between block and plane equals 0.3?

that their solutions require the interrelation of qualitative and quantitative problem representations.

Multi-Component Tests Before and after the instruction as well as after the collaborative problem solving, subjects had to work on parallel tests. The tests were made up of two components which assess knowledge about qualitative and quantitative aspects of classical mechanics. Six items of the first component assess knowledge about qualitative aspects and six items assess knowledge about quantitative aspects. The items were designed in such a way that the solution to each item required the use of information presented in the instructional unit on qualitative or quantitative aspects, respectively.

The six items of the second component were designed in such a way that the solution to each item required the interrelation of qualitative and quantitative problem representations. Thus, while half of the items of the first test component should be solvable after the instruction took place, items of the second test component should only be solvable to a larger extent after the collaborative problem solving took place.

The pretest, the intermediate test, and the posttest were made up of parallel items. In order to avoid the assessment of abilities which are specific to the use of concept maps, concept maps were not included in the tests. Parallel items were designed in such a way that the same knowledge needed to be applied to solve them. However, surface features such as numerical values were varied across parallel items. Within each test, items were arranged in random order.

Subjects 24 female tenth graders from two different high schools volunteered for the study. The subjects were between 16 and 17 years old. They were paid for their participation. All of the subjects had attended classes on basic aspects of classical mechanics. In these classes, the concepts of time, position, displacement, velocity, acceleration, and force had been introduced. The interrelations between these concepts had been described by means of position-time-, velocity-time-, and acceleration-time-diagrams, for example. However, none of the subjects had attended classes on more advanced, Newtonian aspects of classical mechanics as they are in the foreground of this study.

Procedure

The subjects out of the two experimental groups were investigated in pairs. Each pair was composed of subjects from different schools and was investigated for four days running. On the first day, the subjects worked on the pretest, an introduction into the structure of concept maps and the first sections of the instructional units.

While one subject received instruction on qualitative aspects of classical mechanics, the other subject received instruction on quantitative aspects. While they worked on the pretest and the instructional units, subjects had to work on their own and were not allowed to exchange information. However, they were allowed to work collaboratively on the introduction to the structure of concept maps.

On the second day, the subjects worked on the remaining sections of the instructional units and on the intermediate test. Again, subjects had to work on their own and were not allowed to exchange information.

On the third day, the subjects collaborated on three problems (Problem 1, 2, and 3 as shown in Table 1) which demand the interrelation of qualitative and quantitative problem representations. During collaborative problem solving, subjects were allowed to exchange information at their will. The verbal exchange of information was tape recorded. After the subjects finished their collaborative problem solving attempt, they were given feedback about the correctness of their solution. In the case that the solution was incorrect, they were told where an error was made. The solution to the problem, however, was not told to the subjects. At the end of the collaborative problem solving, subjects were allowed to re-read selected sections in the unit which they had received during instruction.

On the fourth day, the subjects collaborated on the remaining problem (Problem 4 as shown in Table 1) under the same conditions as described above. Finally, each subject worked individually on the posttest.

The subjects out of the control group were investigated in groups. They worked on three different days on the pretest, the intermediate test and the posttest. Between two days of testing there was one day without testing. During the study, all subjects were allowed to use a ruler and a calculator. The subjects were not given feedback about their answers to the different tests.

Results

Analysis of the Multi-Component Tests

The average relative solution frequencies of all groups in the first test component of the pretest, intermediate test, and posttest are shown in Figure 1. A two-way analysis of variance with repeated measurements Group x Test was computed. Across groups, the subjects improved significantly from the pretest to the posttest ($F(2, 42) = 70.57$, $p < .001$).

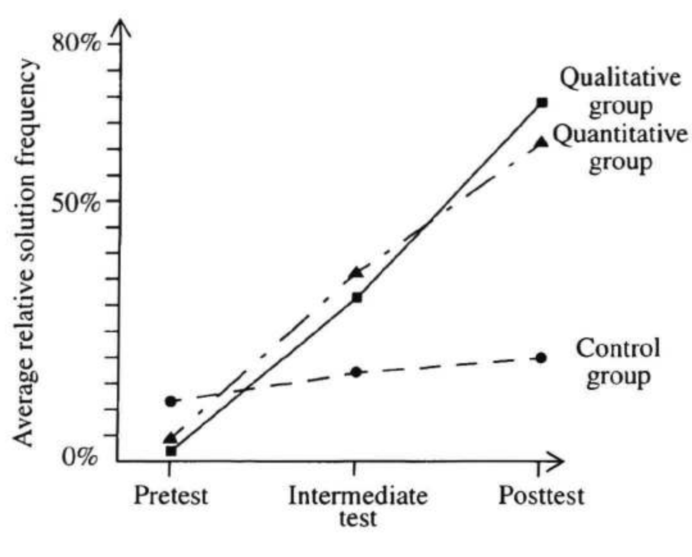

Figure 1: The solution frequencies of all groups in the first component of the pre-, intermediate, and posttest.

The subjects out of the experimental groups gained significantly more from the pretest to the posttest than the subjects out of the control group ($F(4, 42) = 13.05, p < .001$).

At this level of analysis, the subjects out of the experimental groups did not differ significantly in their gains ($F(2, 28) = .68, p = .51$). In their tendency, however, the subjects who initially were taught qualitative aspects of classical mechanics gained more from the information provided by their quantitatively instructed partners during collaborative problem solving than the other way round. While the correctness of the qualitatively instructed subjects increased on average by 36% from the intermediate test to the posttest, the correctness of the quantitatively instructed subjects increased only by 25%.

To make this difference even more visible, the items of the first test component which assess knowledge about qualitative aspects of classical mechanics were analyzed separately from the items which assess knowledge about quantitative aspects. Again, a two-way analysis of variance with repeated measurements Group x Test was computed. The corresponding average relative solution frequencies are shown in Figure 2.

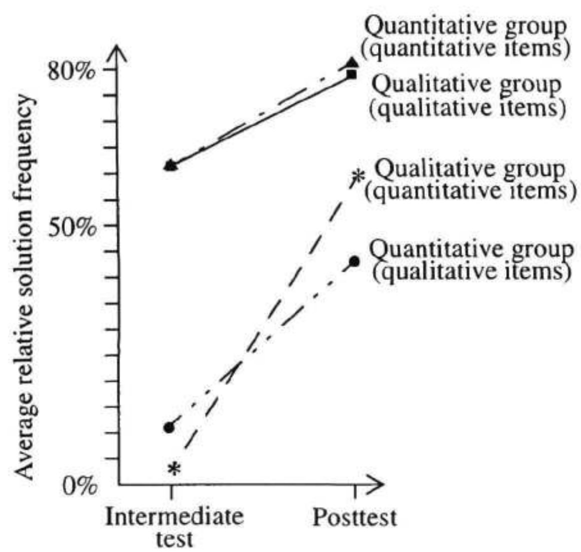

Figure 2: The solution frequencies of the experimental groups in the first component of the intermediate and posttest with respect to the items which assess knowledge about qualitative or quantitative aspects.

The subjects did not differ significantly with respect to how well they were able to consolidate and to extend the knowledge they had acquired during the instruction. However, as predicted, the subjects differed significantly with respect to how well they were able to take advantage of the information provided by their partners during collaborative problem solving ($F(1, 14) = 5.3, p < .05$). The subjects who initially were taught qualitative aspects of classical mechanics gained significantly more from the information provided by their quantitatively instructed partners than the other way round.

The average relative solution frequencies of all groups in the second test component of the pretest, intermediate test, and posttest are shown in Figure 3. A further two-way analysis of variance with repeated measurements Group x Test was computed. As expected, the items of the second test component were only solvable to a larger extent after the collaborative problem solving took place. The subjects out of the experimental groups improved significantly from the intermediate test to the posttest ($F(1, 14) = 9.6, p < .01$).[1]

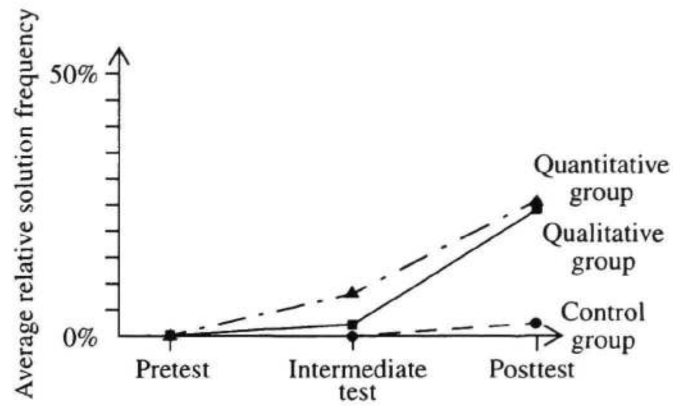

Figure 3: The solution frequencies of all groups in the second component of the pre-, intermediate, and posttest.

Protocol Analysis

Data Analyzed During collaborative problem solving, the subjects' verbal exchange of information was tape recorded. On the basis of the subjects' achievements in the tests, three pairs of subjects were selected. In one pair, both subjects clearly improved from the intermediate test to the posttest. In two pairs, only the qualitatively or the quantitatively instructed subject improved evidently. The tapes which recorded the subjects' work on the first, second, and fourth problem were transcribed. The transcripts were segmented into statements which corresponded more or less to phrases.

The first 200 statements[2] of each transcript were categorized by making use of DISCOUNT (see Pilkington, 1996; Pilkington & Parker-Jones, 1996), a scheme for analyzing dialogue structures as they can be observed during collaborative problem solving and learning.

While we also took advantage of DISCOUNT to describe how successfully learning and less successfully learning subjects differ in their dialogue structures (see Kneser & Ploetzner, 1998), in this paper we report an analysis in which DISCOUNT was applied to categorize whether the subjects' statements address qualitative, quantitative, or interrelations

1. Because in the pretest there was no variance at all observable, we did not conduct a comparable analysis with respect to the pretest and the intermediate test. Subjects out of both experimental groups, however, were able to solve a few items of this test component in the intermediate test. This might be due to pre-knowledge in connection with knowledge acquired during the instruction, for example.

2. The shortest transcript comprised 117 statements, the longest 452 statements.

between qualitative and quantitative aspects of classical mechanics.

Qualitative and Quantitative Aspects in Subjects' Statements Table 2 shows how often the qualitatively and quantitatively instructed subjects requested information during collaborative problem solving which was covered by the instructional unit of their partners. From the first to the fourth problem, the qualitatively instructed subjects gradually made fewer requests for quantitative information. The number of requests for qualitative information, in contrast, raised from the first to the fourth problem.

Table 2: Frequencies of requests for information

	Problem		
Instruction received	1	2	4
Qualitative	33	16	12
Quantitative	4	8	10

How often qualitative aspects, quantitative aspects, or interrelations between both aspects were addressed in the subjects' statements is shown in Table 3. The number of statements which address qualitative aspects and interrelations between qualitative and quantitative aspects clearly increased from the first to the fourth problem with respect to the qualitatively instructed subjects as well as with respect to the quantitatively instructed subjects. In contrast, the number of statements which address quantitative aspects sharply decreased from the first to the fourth problem in both groups.

Table 3: Frequencies of statements which addressed qualitative, quantitative, or interrelations between qualitative and quantitative aspects

	Statements					
	Qualitative		Quantitative		Interrelation	
	Problem		Problem		Problem	
Instruction received	1	4	1	4	1	4
Qualitative	21	36	63	41	3	14
Quantitative	8	29	76	28	7	10

Finally, the number of statements addressing qualitative or quantitative aspects in the first and second half of the categorized statements is presented in Table 4. The frequencies indicate a shift from a continuous emphasis on quantitative aspects in the first problem to an initial emphasis on qualitative aspects followed by an emphasis on quantitative aspects in the fourth problem.

Table 4: Frequencies of statements which addressed qualitative or quantitative aspects in the first and second half of the categorized statements

	Problem					
	1		2		4	
Statements	1. Half	2. Half	1. Half	2. Half	1. Half	2. Half
Qualitative	13	16	33	45	52	13
Quantitative	76	63	37	33	24	45

Discussion

The experimental study described above yielded three main findings. The first finding is that students with initially different but complementary domain representations learn to appropriately interrelate their representations during collaborative problem solving when the students are confronted with problems which require such an interrelation. Because the initially different domain representations demand that each student contributes to the solution of a problem, students are given various opportunities to learn from each other and might be encouraged to construct new relations which bridge the different representations (see Schwartz, 1995).

The second finding is that collaborative problem solving on the basis of different but complementary domain representations supports not only the acquisition of knowledge structures in which different aspects of an application domain are appropriately interrelated (see Slavin, 1995) but also the acquisition of control knowledge. During collaborative problem solving, students gradually shifted their focus from exclusively quantitative problem representations to appropriate sequences of qualitative and quantitative problem representations. However, we are fully aware that the results of our protocol analysis are of rather preliminary nature.

The third finding is that during collaborative problem solving, qualitatively instructed subjects gained more from their quantitatively instructed partners than the other way round. In accord with research on differences between novices and experts, this finding indicates that qualitative problem representations form not only a good starting point for the subsequent construction of quantitative problem representations but also a beneficial starting point for learning quantitative problem representations.

Acknowledgements

This research has been supported by the German National Research Foundation (DFG) under contracts SP 251/9-1 and PL 224/2-2. We thank Rachel Pilkington and Hans Spada for many stimulating discussions about this research and Sieghard Beller for helpful comments on an earlier version of this paper.

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