European Journal of Psychology of Education
1990, Vol. V, n.º 1, 5-19

Towards Powerful Learning Environments for the Acquisition of Problem-Solving Skills

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It is generally agreed that acquiring thinking and problem-solving skills is nowadays a primary objective of general education. Responding appropriately to this challenge requires an answer to the following questions: 1. what does the acquisition of problem-solving skills involve, and 2. how can those abilities be fostered through systematic instruction? This contribution describes a four-step model of skilled problem-solving processes, and gives an overview of three major categories of cognitive skills involved in competent problem solving, namely, the flexible and integrated application of domain-specific knowledge, of heuristic methods, and of metacognitive skills. Furthermore, a framework is presented for the design and elaboration of powerful teaching-learning environments in which such problem-solving skills can be acquired efficiently. Two basic ideas underlying this model are: the view of learning as a constructive process, and the idea of cognitive apprenticeship as an effective and appropriate method for learning and teaching. Finally, some recent research findings supporting the educational significance of the framework are briefly reviewed.

Introduction

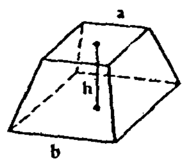
A domain of inquiry that has tremendously grown over the past ten to fifteen years is the so-called cognitive science (Gardner, 1985; Pylyshyn, 1984). The well-known American psychologist George Miller (1984) has colorfully dubbed the object of cognitive science as the study of the «informavores», including the higher vertebrates and certain computer systems. For quite a number of humans, being considered as a relative of the computer is probably even worse than belonging to the same family as the monkey. However, it is certainly true that being able to process, organize, and retrieve information with a view to problem solving represent essential skills of every individual in our complex societies, in which information has become the major kind of raw material. Consequently, it is generally agreed that acquiring problem-solving ability is nowadays a primary educational objective. In Resnick's (1987a) terms, one could say that while in a preceding era mass education focussed on «low literacy», i.e. the acquisition of basic skills of reading, computation, health, and citizenship training, it has now become an educational challenge to aim at «high literacy» for all students.

Responding appropriately to this challenge requires an answer to the following two questions: 1. what does the acquisition of problem-solving skills involve, and 2. how can those abilities be enhanced through systematic instruction? In fact, both questions are strongly related in the sense that solving the second one requires a clear answer to the first query. In this contribution I will argue that the present-state-of-the-art of cognitive research in general, and cognitive instructional psychology in particular, offers some promise in providing appropriate answers to those questions. To do so I will refer to the results of recent research. However, I will first describe a four-stage model of competent problem solving.

A model of competent problem solving

In order to describe the problem-solving model I start from an example borrowed from Polya's (1968) work in mathematics education. Suppose that we present the following task to a student: Find the volume of the following geometric figure which has a square base, given the height (h), and the length of the side of both the upper surface (a) and the base (b) (see Figure 1).

Figure 1. Tâche concernant le volume d'un tronc de pyramide



Note. a=Upper base; b=Lower base; h=height

Figure 1. Task concerning the volume of a frustrum

Let us also assume that this task confronts our student with a real problem; this means that he realizes he cannot immediately give the answer, and does not have a ready-made solution available, but at the same time he knows that the task probably contains the information necessary to find the solution.

The first stage in a skilled problem-solving process now consists in constructing an *appropriate* initial representation of the problem, i.e. a cognitive structure corresponding to a problem that is built by the problem solver. For most problems different representations are possible, wrong ones as well as correct ones, and, as far as the correct ones are concerned, more appropriate and less appropriate alternatives. One can say that constructing a suitable problem representation in the beginning of the solution process constitutes an essential aspect of understanding the task. In our example (see Figure 1) a proper initial representation consists in conceiving the given figure as the frustrum of a right pyramid (PR1).

In the second stage the initial problem representation (PR1) is transformed until a new representation is obtained for which the problem solver has an immediate and ready-made solution (PR2). In other words, the initial problem has been transformed to the point where it has reached the form of a routine task. In our example this phase could proceed as follows:

- Is there a related problem for which I can find the solution immediately? Yes: I can calculate the volume of a right pyramid.
- Taking this into account, can I restate or transform the initial task? Yes: when I consider the frustrum as part of the complete pyramid (see Figure 2), I can find its volume by calculating the difference between the large and the small pyramid.

*Figure 2.*Représentation transformée de la tâche concernant le volume d'un tronc de pyramide

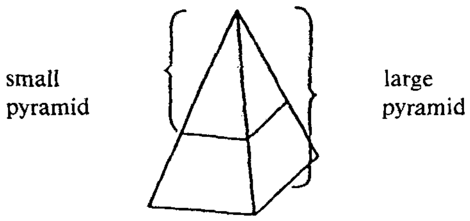


Figure 2. Transformed task concerning the volume of a frustrum

The third stage in the problem-solving process involves the elaboration of the solution (S) of the *routine task* (RT) using the appropriate domain-specific knowledge. In our example this consists mainly in applying the formula for calculating the volume of a pyramid:

$$\frac{\text{Base}^2 \times \text{Height}}{3}$$

Finally, in the verification stage (V) certain actions are performed to check the correctness of the solution found in the preceding phase.
The entire solution process is represented schematically in Figure 3.

Figure 3. Schéma du processus de résolution du problème

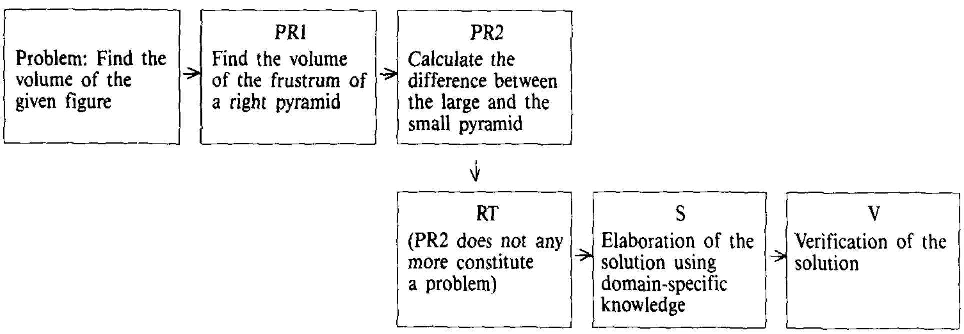


Figure 3. Schematic representation of the solution process

Taking into account this overview of the entire solution process we can ask the following question: what kinds of skills should a problem solver master with a view to approaching a problem appropriately and with a good chance of being successful? An analysis of the vast literature relating to this topic reveals that competent problem solving requires mastery of three categories of skills:

1. flexible application of a well-organized domain-specific knowledge base, involving concepts, rules, principles, formulas, and algorithms;
2. heuristic methods, i.e. systematic search strategies for problem analysis and transformation;
3. *metacognitive skills*, involving knowledge concerning one's own cognitive functioning on the one hand, and activities that relate to the self-monitoring and regulation of one's cognitive processes on the other.

I will discuss each of these components in detail, starting from the argument that learning to solve problems consists of the integrated acquisition and application of those three categories of skills. A similar viewpoint was recently taken by Perkins and Salomon (1989).

Heuristic methods

Early studies in laboratory settings using mainly knowledge-lean tasks, and applying thinking aloud and retrospection as data-gathering techniques have convincingly shown the heuristic nature of human problem solving (Newell & Simon, 1972). Heuristic methods are intelligent and systematic search strategies. They do not guarantee that one will find the solution of a given problem. However, because they induce a systematic and planned approach of the task — in contrast to a trial-and-error strategy — heuristic methods substantially increase the probability of success in solving the problem. Some examples of heuristic methods are: carefully analyzing a problem specifying the knowns and the unknowns; decomposing the problem into subgoals; finding an easier related or analogous problem; visualizing the problem using a drawing or diagram; working backward from the intended goal or solution; provisionally relaxing one of the constraints of the solution, returning later to reimpose it. An important quality of these heuristics lies in their general character, i.e. they can be applied as solution strategies in different content domains.

In the solution process of the frustrum problem described above one of the heuristics just mentioned was applied, namely finding an easier related problem for which one can immediately find the solution. This example illustrates at the same time the function of such heuristic methods in a problem-solving process, namely the transformation of the initial problem representation until a representation of the task emerges which constitutes a familiar routine task for the problem solver.

The available research carried out in a variety of content domains shows that heuristics can be taught successfully (see e.g. Nickerson, Perkins & Smith, 1985). However, the same literature obviously shows that acquiring heuristic strategies within a certain content domain does not spontaneously improve one's ability to solve problems in other content domains for which those strategies are appropriate (see also Pressley, Snyder & Cariglia-Bull, 1987).

One of the most representative examples of heuristics teaching is the work of Schoenfeld (1985) in the domain of mathematics. He starts from the well-documented finding that using a set of heuristics, as well as a control strategy for their application, constitutes an essential component of expert problem solving. It is important to remark here that according to Schoenfeld it is not sufficient to teach students isolated heuristics, because they often are unable to decide which method is appropriate for the problem at hand. Therefore, it is necessary to teach heuristics within the context of a control strategy that helps the learner to select the right heuristic to solve a given problem. In that perspective Schoenfeld has proposed such a strategy, consisting of five stages.

1. Analysis oriented towards understanding the problem by constructing an adequate representation.
2. Design of a global solution plan.
3. Exploration oriented towards transforming the problem into a routine task. This stage constitutes the heuristic heart of the strategy.
4. Implementation or carrying out the solution plan.
5. Verification of the solution.

The resemblance between this strategy and the stages of the general model of competent problem solving described earlier is obvious. Consequently, its applicability is not restricted to mathematics. Although the exploration stage is the heuristic heart of the strategy, a variety of heuristics can also be used appropriately in the analysis as well as in the verification stage (Schoenfeld, 1985, p. 109).

In a series of studies with college students, in which much attention was paid to the elaboration of a powerful learning environment, Schoenfeld has provided support for the teachability of his control strategy, and the heuristics involved. In the final section of this article, I will discuss in detail the dimensions of such a powerful learning environment.

Domain-specific knowledge

As said before, the early studies of problem solving focussed on knowledge-lean tasks. But in the mid-seventies the question has been raised whether the principles underlying the solution of this kind of tasks, can be generalized to problems in semantically rich domains. Consequently a large number of investigations were carried out in a variety of fields such as physics, mathematics, computer programming, medical diagnosis, economy, etc. In the preceding section it has already become obvious that competent problem solving in such domains involves the application of heuristic strategies. However, a major complementary finding of this research is that expert problem solvers also master a large and well-organized domain-specific knowledge base (see e.g. Glaser, 1987). Substantial evidence in this respect derives from the so-called expert-novice studies.

A representative example of this is an investigation by Chi, Feltovich, and Glaser (1981) in physics. They asked expert physicists (advanced graduate students) and novices (undergraduate students) to sort and classify mechanics problems. The novices based their classification on the apparatus involved (lever, inclined plane, balance beam), on the actual terms used in the problem statement, or on the surface characteristics of the diagram presented. Experts, on the contrary, classified problems according to the underlying physics principles needed to solve them (e.g. energy laws, Newton's second law). In other words, the experts constructed a totally different initial representation of the problems than the novices, reflecting differences in the content as well as in the organization of the knowledge base of both groups. It needs no argument that the quality, the completeness, and the coherence of the initial representation determine the efficiency of the rest of the solution process.

When describing the competent problem-solving model in a previous section I have indicated that subject-matter knowledge intervenes in the third stage of the process, consisting of the elaboration of the solution of a routine task. The investigation by Chi and her co-workers illustrates a second important function of domain-specific knowledge, namely its role in the construction of the representation of the problem.

The important influence of conceptual knowledge has been demonstrated in a large variety of domains, such as musical composition and painting. Hayes (1985) for example carried out an extensive biographical study of 76 composers and 132 painters. He reported that in both fields a high level of productivity and creativity occurs at the earliest after a learning period of 6 to 10 years during which large amounts of knowledge and techniques are acquired.

In our own work we have found that conceptual domain-specific knowledge also strongly affects the solution processes of young children on arithmetic word problems (De Corte & Verschaffel, 1985, 1987). In one longitudinal study 30 first graders were individually interviewed three times during the school year: at the very beginning, in January, and in June at the end of the school year. Each time they were given eight word problems which differed according to their semantic structure. There were four addition and four subtraction problems, and both categories involved two change problems, one combine problem, and one compare problem. Within those three types further distinction can be made depending on the identity of the unknown quality. For example, in the combine problem in Table 1 the super set or whole is unknown; however, this problem can be restated in such a way that one of the subsets or parts is unknown: «Pete has 3 apples; Ann has some apples too; together Pete and Ann have 10 apples; how many apples does Ann have?»

Table 1
Results of 30 first graders on three addition word problems in the beginning of the school year

Problem	Semantic structure	Number of correct solutions
1. Pete has 3 apples; Ann has 7 apples; how many apples do they have altogether?	Combine: superset unknown	26
2. Pete had some apples; he gave 3 apples to Ann; now Pete has 5 apples; how many apples did Pete have in the beginning?	Change: startset unknown	12
3. Pete has 3 apples; Ann has 6 more apples than Pete; how many apples does Ann have?	Compare: compared set unknown	5

Tableau 1
Résultats de 30 élèves au début de la première année du primaire à trois problèmes verbaux d'addition

Table 1 shows that during the first interview, in the beginning of the school year, there were substantial differences in the level of difficulty between the three problems. Yet, these problems can be solved by the same arithmetic operation, namely by adding the two given numbers. However, their semantic structure is quite different. Similar results were found for subtraction problems. From these findings we can derive that solving even those simple word problems requires more than mastering the basic arithmetic operations of addition and subtraction. Besides, children must have the necessary conceptual knowledge to understand and represent the problems appropriately. More specifically they should have acquired the change, combine, and compare problem schemata; schemata are conceived as theoretical constructs describing the content and format of an organized body of knowledge in memory, in this case knowledge of the semantic structure of simple word problems.

The robust finding that skilled problem solving in a given domain — in humans as well as in computers — depends to a large extent on the availability of a well-organized and flexibly accessible knowledge base, is one of the major reasons underlying the scepticism concerning the possibility of enhancing problem-solving ability across domains through the mere teaching of general heuristic and metacognitive strategies. Indeed, when confronted with a problem in a relatively unfamiliar domain, the problem solver lacking sufficient domain-specific knowledge often does not know how to use the heuristics that he has in his repertoire, because he is unable to find the link between the problem situation and the appropriate heuristic that applies to it. Therefore, general heuristics are nowadays referred to as weak methods (Perkins & Salomon, 1989).

Metacognitive knowledge and skills

Recent research has more and more convincingly shown the importance of this third category of knowledge and skills in competent problem solving. Metacognition involves knowledge concerning one's own cognitive functioning on the one hand, and activities relating to the self-monitoring of one's cognitive processes on the other (Brown, Bransford, Ferrara & Campione, 1983; Simons & Beukhof, 1987).

Metacognitive knowledge includes knowing about the strengths as well as the weaknesses and limits of one's cognitive capacities. For example, being aware of the limits of short-term memory, knowing that our memory is fallible but that one can use aids (such as mnemonics) for retaining certain information. But metacognitive knowledge also involves naive, often incorrect, and motivationally important beliefs and convictions. This is illustrated by the work of Garofalo (1985) and Schoenfeld (1988), showing among other things that less skilled students are afflicted with strange opinions like: being able to solve a problem is a mere question of luck; when you have not found the solution of a problem after just a few minutes, it is useless to spend more time on it, and, therefore, you better quit. Even more important in this respect are the findings of Dweck and Elliott (1983). According to these authors, the specific actions individuals will take in a learning or problem-solving situation depend on the particular conception about ability they hold. They found two very different conceptions of ability, or «theories of intelligence» in children. The entity conception considers ability as a global, stable, and unchangeable characteristic reflected in one's performance, whereas the incremental conception treats ability as a set of skills that can be expanded and improved through learning and effort. It is obvious that both groups will have different motivations for, and approaches to new learning tasks and problem situations.

The self-monitoring or self-regulation mechanisms that constitute the second component of metacognition can be defined as the executive control structure that organizes and guides our learning and thinking processes. This includes skills such as planning a solution process; monitoring an ongoing solution process; evaluating and, if necessary, debugging an answer or a solution; and reflecting on one's learning and problem-solving activities.

Evidence supporting the importance of metacognition for learning and problem solving has been obtained in comparative studies of skilled and weak problem solvers in different content domains, such as reading comprehension (Garner, 1987), and mathematics (Garofalo, 1985). Therefore, it is not surprising that more and more voices are heard demanding more explicit attention to metacognitive skills in instruction. For example, Norman (1980) has phrased this as follows:

> «It is strange that we expect students to learn yet seldom teach them anything about learning. We expect students to solve problems yet seldom teach them about problem solving. And, similarly, we sometimes require students to remember a considerable body of material yet seldom teach them the art of memory. It is time we made up for this lack, time that we developed the applied disciplines of learning and problem solving and memory. We need to develop the general principles of how to learn, how to remember, how to solve problems, and then to develop applied courses, and then to establish the place of these methods in an academic curriculum» (p. 97).

Furthermore, the available research has already shown that it is quite possible to teach metacognitive skills successfully. In fact, Schoenfeld's (1985) heuristic teaching in mathematics discussed above offers a first illustration in this respect. Indeed, Schoenfeld taught the heuristics within the framework of a control strategy that helps the student to select the appropriate heuristic for the problem at hand. Using this control strategy constitutes a metacognitive skill.

In the domain of reading, Palincsar and Brown (1984) have demonstrated that teaching poor readers of the seventh grade (approximately 13-year olds) metacognitive skills can lead to increases in text comprehension, as well as students' monitoring of their comprehension. Using reciprocal teaching, the children were taught four comprehension-fostering strategies: summarizing a text; questioning, i.e. stating potential test questions about the content; asking for clarification when necessary; and making predictions concerning the content of the following section. Reciprocal teaching was inspired by the work of Vygotsky (1962) and was done in the form of a dialogue in which a teacher and two students took turns leading a discussion concerning segments of the text. Progressively the learners' contribution to and responsibility for the dialogue was increased.

Characteristics of powerful learning environments

In the previous sections I have identified and described three categories of skills that learners must acquire in order to become skilled problem solvers. I have also briefly referred to teaching experiments showing that heuristic methods and metacognitive skills can be taught successfully. An important question from an instructional point of view is now: what are the major dimensions and features of learning environments that are effective in promoting those skills in students? Starting from a moderate constructivist conception of learning, and on the basis of recent research including our own empirical work, I argue that such powerful learning environments are characterized by a good balance between discovery learning and personal exploration on the one hand, and systematic instruction and guidance on the other, always taking into account the individual differences in abilities, needs, and motivation between students. A recent paper by Collins, Brown, and Newman (in press; see also Brown, Collins & Duguid, 1989) presents an interesting framework for the further elaboration and evaluation of such powerful learning environments.

Collins et al. (in press) also start from the assumption that learning is basically a constructive process: students are not passive recipients of information, but they actively construct their knowledge and skills through interaction with the environment, and through reorganization of their own mental structures. A second underlying idea of their framework is the (cognitive) apprenticeship view of teaching and learning which embeds the acquisition of knowledge and skills in the social and functional context of their use (see also Resnick, 1987b).

Against this background, Collins et al. (in press) have thoroughly analyzed three successful models of cognitive apprenticeship, namely Palincsar and Brown's (1984) reciprocal teaching of reading comprehension, Scardamalia and Bereiter's (1985) procedural facilitation of writing, and Schoenfeld's (1985) heuristic teaching of mathematics. Their analysis resulted in a general model for designing learning environments involving four dimensions: content, method, sequence, and sociology.

With respect to content an ideal learning environment should focus on the acquisition of all categories of knowledge that experts master and apply. In addition to the three categories discussed in this paper, namely domain knowledge, heuristic method, and metacognitive strategies, Collins et al. (in press) mention a fourth type of knowledge that experts have and apply, namely learning strategies, i.e. strategies for acquiring any of the three other types of content (see e.g. Weinstein & Mayer, 1986).

With a view to helping students to acquire and integrate those different categories of knowledge and skills the teacher can apply six different methods falling roughly into three categories.

1. Three techniques constituting the heart of cognitive apprenticeship, are based on observation, guided and supported practice, and feedback; they aim at the acquisition of an integrated set of cognitive and metacognitive skills:

- modelling involves the observation by the student of an expert who is performing a certain task; this allows the student to construct an appropriate mental model of the activities that are required for skilled performance;
- coaching refers to the observation of the student by the teacher during task execution as a basis for giving hints and feedback with a view to improving performance;
- scaffolding consists of providing direct support to the student while he is carrying out the task; this method derives from the Vygotskyan concept of the zone of proximal development (Vygotsky, 1978).

2. Two other methods aim at making students explicitly aware of their own cognitive and metacognitive activities:

- articulation refers to any technique that helps students to spell out and make explicit their knowledge and problem-solving procedures;
- reflection leads students to compare their own cognitive strategies and solution processes with those of experts, of other learners, and ultimately, with a mental model of expert performance.

3. Exploration, finally, intends to increase the learner's autonomy in skilled problem solving as well as in discovering, identifying, and defining new problems.

A seventh method can be added to this series of teaching strategies, namely generalization, consisting of showing explicitly to students how certain cognitive strategies acquired in one domain can be appropriately used to solve problems in another domain. It is obvious that this method aims at the facilitation of the transfer of cognitive skills.

Collins et al. (in press) present two principles relating to the sequencing of learning tasks:

1. progressive complexity and diversity, such that competent performance requires more and more of the domain-specific knowledge as well as a larger variety of cognitive and metacognitive skills;
2. global before local skills, involving that the orientation towards the complex task as a whole should precede the practicing of partial, lower-level skills.

Finally, the authors describe a series of guidelines that are important with a view to realizing a favorable social context for learning:

1. situated learning involving that students should be given tasks and problems representing the diversity of situations to which they will have to apply their knowledge and skills afterwards;
2. organizing opportunities for contact with and observation of experts;
3. enhancing intrinsic motivation for learning;
4. fostering cooperative learning through small group problem solving;
5. organizing classroom dialogues aiming at the identification, analysis, and discussion of students' problem-solving strategies and processes.

Research findings supporting the apprenticeship framework

Additional research is necessary to test the validity of this apprenticeship view of teaching and learning cognitive skills. However, already now there is evidence available supporting major components of the framework. For example, Schoenfeld's (1985) successful approach, mentioned above, for teaching a control strategy for mathematics problem solving involving a series of heuristics, embraces numerous elements described by Collins et al. (in press). From the start Schoenfeld orients his students towards the control strategy as a whole, although in a schematic form. Then, the different stages of the strategy — analysis, design, exploration, implementation, and verification — are discussed consecutively, and the corresponding heuristics are explained and practiced. In this respect, modelling is extensively used to demonstrate how an expert selects and applies heuristic methods. Afterwards, the students themselves are given ample opportunities to apply those methods under the guidance of the teacher who encourages them to use certain heuristics, gives hints, provides immediate feedback, and, if necessary, helps with the execution of some parts of the task which the student cannot carry out autonomously yet. Besides modelling and class teaching, Schoenfeld also frequently uses small group problem solving. Acting himself as a consultant he regularly asks three questions during group activities: 1. what are you doing, 2. why are you doing this, and 3. if what you are doing now is successful, how will it help to find the solution? Asking these questions serves two purposes: it encourages students to articulate their problem-solving strategies, and to reflect on those activities. Schoenfeld's ultimate goal is that students spontaneously ask the three questions themselves, and in doing so regulate and monitor their own thinking processes.

In a project on «Computers and Thinking» we have recently been working on the development, implementation and evaluation of a powerful Logo learning environment, aiming at the acquisition and transfer of general cognitive skills (De Corte, Verschaffel, Hoedemaekers, Schrooten & Indemans, 1988; De Corte, Verschaffel, Schrooten, Indemans & Hoedemaekers, 1989). Taking into account the available research literature we assumed that the transfer of thinking skills can be achieved when at least two of the following three conditions are fulfilled: 1) the pupils have acquired sufficient domain-specific knowledge, i.e. mastery of the Logo primitives and concepts; 2) they have achieved a sufficient level of mastery of the intended thinking skills in the context of Logo programming; 3) the pupils have explicitly and intentionally learned to apply those thinking skills in at least one other content domain. More specifically, the following hypothesis was stated: when the first two conditions are fulfilled transfer occurs; fulfilment of the third condition enhances the transfer effect.

During the school year 1987-1988 a systematic experiment was carried out in three sixth grade classes of 24 children each, according to the pretest-posttest design with control group. Two classes served as experimental groups (E1 and E2), and the third one as a control group. In E1 the fulfilment of the first two transfer conditions mentioned above was pursued; in E2 fulfilment of all three conditions was aimed at. The control class was a non-treatment group. In both experimental groups a Logo-course was taught one afternoon a week during the whole school year (approximately 60 hours); the class was equipped with nine Philips MSX-computers.

In order to realize the second transfer condition — i.e. mastery of a sufficient level of programming skill — the major component of the Logo course was the explicit training of two heuristic skills, namely *problem decomposition* and *constructing an external representation* of a problem, within the framework of a systematic metacognitive strategy for writing Logo programs focussing on *planning* and *debugging*. More specifically the programming strategy consisted of two main phases with different steps each: a planning phase carried out independently from the computer, and an integrated coding and testing phase on the machine.

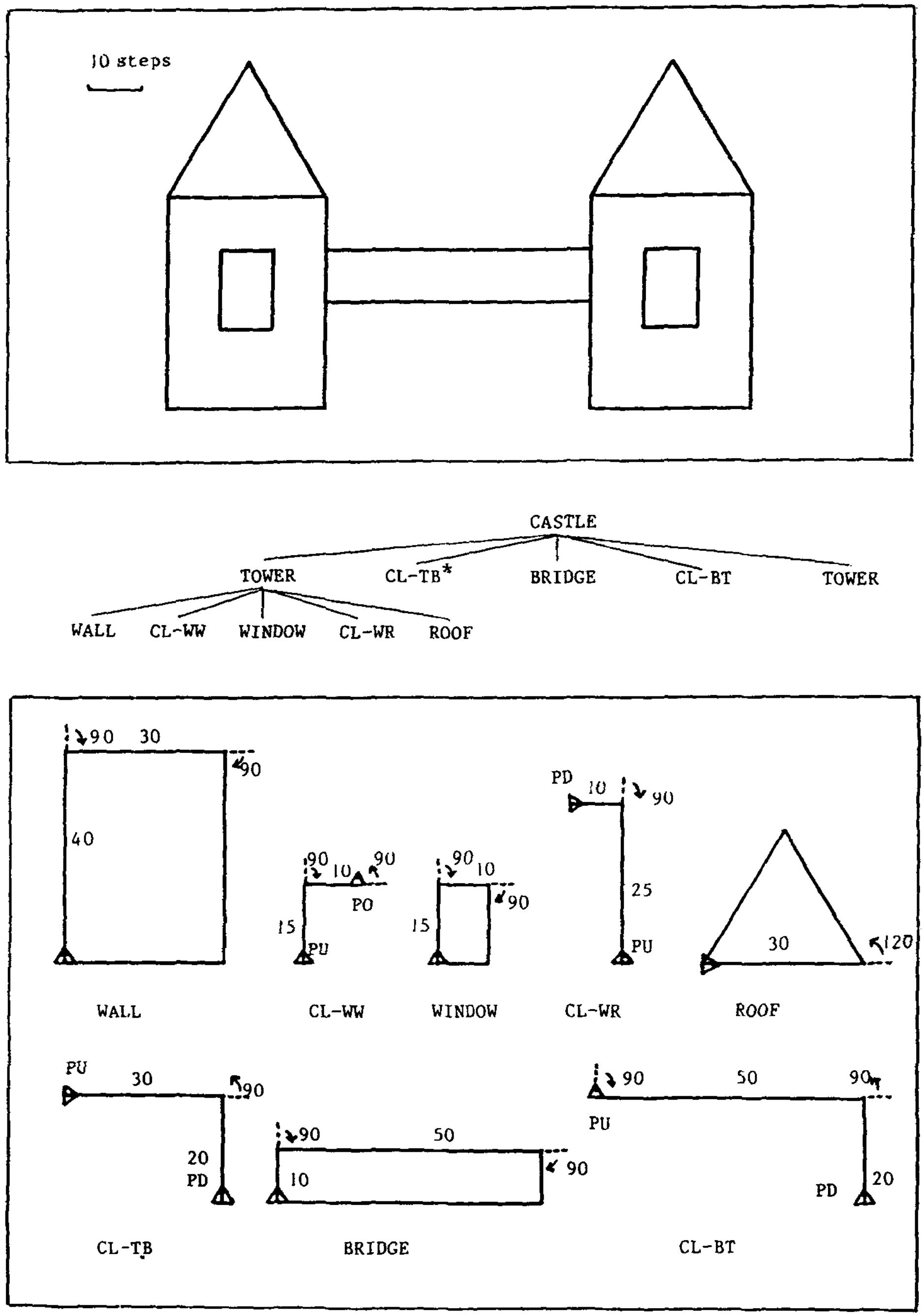
In the planning phase three steps involving the heuristic strategies are distinguished (see Figure 4): 1) making a drawing of the intended screen effect; 2) constructing a tree-like diagram in which the complex drawing is subdivided into easy-to-program building blocks; this diagram involves at the same time the sequence in which the different parts have to be drawn; 3) making separate drawings of the different parts, indicating for each one the lengths and angles as well as the start and end position of the turtle.

Once the planning is completed, the coding and testing phase can begin. This activity is guided by two principles: 1) top-down programming, involving that the children are taught to start with the most global procedure for the drawing, called the «mother-procedure», which consists of the names of the subsequent parts from the highest level of the tree-like diagram; subsequently they specify each component of this procedure until the lowest level of the diagram is reached; 2) immediate testing of each new procedure after defining it by calling the «mother-procedure»; consequently the result appears on the screen, so that it can be evaluated, and, if necessary, debugged.

In one of the two experimental classes (E2) explicit instruction for transfer was provided by teaching a five-week course in arithmetic word problem solving, in which the same general solution strategy was trained, adapted to this specific domain.

In line with our conception of a powerful learning environment the teaching in both experimental classes was characterized by a good balance of exploratory learning activities on the one hand, and systematic instruction aiming at mastery of the intended domain-specific concepts and the programming skills on the other (transfer conditions 1 and 2). In this respect our learning environment involved major aspects of the Collins et al. (in

Figure 4. Plan pour la rédaction d'un programme Logo pour dessiner un château



* Connecting Link between Tower and Bridge

Figure 4. Plan for writing a Logo-program for drawing a castle

press) framework. The programming strategy was first demonstrated as a whole by a member of the research team, and the different steps were explained with a view to helping students to build a conceptual model of the processes that are required to carry out the task (modelling). Then, each component of the strategy was treated and practiced separately; the teacher provided support where necessary (scaffolding). Finally, the children were given ample opportunity to practice the whole strategy in small groups of three pupils working on progressively more difficult problems. In the beginning the groups were guided intensively using hints, feedback and support (coaching, scaffolding), but the interventions were removed gradually as children's mastery of the skills increased (fading).

The results of this study show that it is possible to teach twelve-year-olds a metacognitive strategy for programming, involving the systematic application of heuristic methods such as decomposing a problem into subgoals, and they also demonstrate that mastery of those cognitive skills within the domain of Logo programming is sufficient to achieve near transfer. Those outcomes can be summarized as follows (see De Corte, Verschaffel, Schrooten, Indemans & Hoedemaekers, 1989 for more details).

The scores on a Logo knowledge test revealed that the pupils of both experimental classes had acquired a good understanding of the Logo primitives and concepts.

Three tests were carried out to assess mastery of the programming strategy. Two tests dealt with the construction of a tree-like diagram (initial stage of the strategy), while a third one concerned the integrated coding and testing phase (second stage). The results on the tests about the initial stage revealed that by the end of the experiment most children had reached the predetermined mastery criterion. In the first test, the children were given a set of drawings with two tree-like diagrams, one of which contained a mistake; in E1 and E2 respectively 19 and 23 out of the 24 pupils were sufficiently able to indicate the correct diagrams. The second test consisted of drawing a tree-like diagram for a complex figure (a submarine); the results showed that in E1 and E2 respectively 20 and 19 out of the 24 children mastered the skill of constructing autonomously an appropriate diagram.

On the test concerning the second stage of the programming strategy, the results were positive too. When asked to write a Logo program for a relatively complex drawing starting from a given plan, 20 children in E1 and 22 in E2 were able to apply the instructed strategy efficiently. They used the top-down programming style fairly consistently; when a new procedure was defined, it was tested by calling the mother-procedure; and when an incorrect screen effect was obtained, detection, analysis and debugging of the programming error was performed in a systematic and straightforward way.

In the experimental class in which the children where explicitly taught to apply the planning and debugging skills in another domain, the third transfer condition was not sufficiently achieved. Although 22 out of the 24 pupils were fairly skillful at choosing the correct tree-like diagram for arithmetic word problems, and at solving problems starting from a given diagram, only 10 of them were able to construct themselves an appropriate diagram for a given word problem. Consequently a conclusive test of the second part of the hypothesis stated above, namely, that fulfilment of the third condition enhances transfer, becomes impossible in the present study. Therefore that aspect of the investigation will be left out of consideration in the following summary of the transfer results.

Five tests were administrated to measure transfer of the four thinking skills taught in the Logo course: planning and debugging — two metacognitive aspects —, and problem decomposition and constructing an external representation — the two heuristic strategies. They consisted of tasks related neither to Logo nor to arithmetic word problems; e.g. a maze test for assessing children's planning skill, and a test involving detection and correction of errors in a series of written instructions for measuring the skill in debugging (see Mc Coy Carver, 1988). The major technique for data analysis was a MANOVA mixed design. The transfer results for three out of the four skills, namely debugging, problem decomposition, and construction of an external representation, showed that the Logo treatment was successful in achieving transfer, especially to situations that are not too different from the original learning context. This result is in line with the outcomes of several other recent investigations (see e.g. Littlefield, Delclos, Lever, Clayton, Bransford & Franks, 1988; Shultz, McGilly, Pratt & Stafford Smith, 1986). Stated in terms of the conditions for transfer underlying the present investigation, our findings mean that fulfilment of the first two conditions — knowledge of the Logo primitives and concepts, and mastery of the intended thinking skills within the Logo environment — is sufficient to achieve near transfer.

Conclusion

Resnick (1983) has distinguished three major components in a theory of instruction: a theory of expertise, an acquisition theory, and an intervention theory. In the past the greatest progress was made with respect to the first component; e.g. expert-novice studies in many content domains have contributed substantially to clarify the role of domain-specific knowledge in problem solving. Actually, the first part of this paper reflects this progress with respect to the issue of problem solving. Because both other parts of a theory of instruction were less well developed, it is important that during this decade researchers have shown an increasing interest in the study of learning processes and intervention strategies.

With respect to a theory of acquisition a number of characteristics of learning processes — although mostly not entirely new — have become more and more research-based; e.g. the constructive nature of learning, the zone of proximal development, the importance of prior knowledge in general, and of children's informal knowledge and skills in particular (e.g. in arithmetic) as a starting point for acquisition processes, the need to anchor learning in real life experience and to provide learning tasks that are representative of the multiple situations in which knowledge will have to be used later on, the progressive internalization and formalization as a guiding principle for acquiring new knowledge and skills (e.g. in mathematics), the influence of beliefs and of motivation on learning, and the resistance of cognitive skills to transfer.

A number of important teaching experiments reported over the past six years mark the increasing interest in the development of an intervention theory which can guide the design of powerful learning environments. Collins, Brown, and Newman's (in press) cognitive apprenticeship model that emerged from this research, provides an appropriate framework for further work aiming at the identification of critical components of such learning environments, i.e. those aspects that encourage children's exploratory learning activities, providing at the same time sufficient guidance to make sure that correct and useful knowledge and skills are constructed.

However, notwithstanding the progress made lately, we must recognize that in many respects the domain is still in its infancy. Indeed, a substantial amount of further research has to be done before we will have a more thorough and precise understanding of, for example, the processes and mechanisms underlying how children construct their knowledge and skills, or of the interaction between cognition and motivation, between skill and will (Paris, 1988) during learning, etc. Similarly, much additional inquiry is necessary to clarify in detail the influence of different teaching methods and instructional situations on the students' acquisition processes.

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Vers le développement d'environnements d'apprentissage efficaces pour l'acquisition de capacités à résoudre des problèmes

De nos jours, on admet généralement que l'acquisition des capacités de pensée et de résolution de problèmes constitue un objectif primordial de l'éducation. Répliquer de façon appropriée à ce défi requiert une réponse aux questions suivantes: 1. qu'implique l'acquisition de capacités à résoudre des problèmes, et 2. comment peut-on influencer l'acquisition de ces capacités par un enseignement systématique?

Cette contribution propose un modèle à quatre phases de processus maîtrisés de la résolution de problèmes. Elle donne un aperçu des trois catégories principales de capacités cognitives qui interviennent dans une résolution compétente de problèmes, notamment l'application flexible et intégrée d'un domaine de connaissance spécifique, de méthodes heuristiques et de capacités métacognitives. On décrit ensuite un cadre de référence pour le développement et l'élaboration d'environnements d'apprentissage efficaces pour l'acquisition de ces habiletés. Deux idées sous-tendent ce modèle: la conception de l'apprentissage comme un processus constructif et l'idée du «cognitive apprenticeship» comme une méthode efficace et appropriée à l'apprentissage et à l'enseignement. Finalement, quelques résultats récents de recherche viennent appuyer l'importance de ce modèle de référence dans l'éducation.

Key words: Problem-solving, Teaching thinking skills, Learning environment, Cognitive apprenticeship, Logo.

Revision received: May 1989

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Current theme of research:

Analysis and improvement of primary school children's problem-solving skills in mathematics. Development of powerful computer-based learning environment for the acquisition of thinking skills.

Most relevant publications in the field of Educational Psychology:

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