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Types of knowledge and their relations to problem solving in science: directions for practice

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Abstract:

This paper presents an overview of research into types of knowledge that are involved in problem solving and how they affect the performance of problem solvers. Some of the types of knowledge discussed are those of declarative, procedural, schematic, strategic, situational, and metacognitive and problem translating skills. Based on this discussion, directions for the enhancement of instruction in problem solving are suggested.

Key words:

Science education, Problem-solving, Knowledge types, Instructional measures.

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INTRODUCTION

Problem solving plays a crucial role in the science curriculum and instruction in most countries (Gabel & Bunce, 1994; Heyworth, 1999; Lorenzo, 2005). It is a much-lamented fact that students often do not succeed in applying knowledge which they have acquired in lessons given in school or in everyday contexts. This circumstance seems to apply especially to science lessons (Friege & Lind, 2006). As a consequence, improving students' problem solving skills continues to be a major goal of science teachers and science education researchers.

Researchers like Beyer (1984) e DeBono (1983) found that mastery of generalized problem solving skills did not differentiate well between good and poor problem solvers. In fact, they concluded that knowledge of context was the most critical feature of problem-solving. Thus, current research supports problem solving as a situational and context-bound process that depends on the deep structures of knowledge and experience (Palumbo, 1990). In order to improve pupils' ability to solve problems in science, special attention should be paid to two main issues (Lee *et al.*, 2001): to develop in students problem solving skills through science education, and to look at the difficulties faced by students in this area and find ways to help them overcome these difficulties. The literature suggests that success in problem solving depends on a combination of strong domain knowledge, knowledge of problem-solving strategies, and attitudinal components (Jonassen, 2000; O'Neil & Schacter, 1999).

The purpose of this paper is threefold: a) To present an overview of a number of types of knowledge involved in problem solving in science; b) to show how these types of knowledge mediate the performance of problem solvers; and c) to suggest some directions for classroom instruction to facilitate more effective problem solving.

TYPES OF KNOWLEDGE INVOLVED IN PROBLEM SOLVING IN SCIENCE: AN OVERVIEW

The knowledge needed to solve problems in a complex domain is composed of many principles, examples, technical details, generalizations, heuristics, and other pieces of relevant information (Stevens & Palacio-Cayetano, 2003). The development of a knowledge base is important both in terms of its extent and its structural organisation. To be useful, students need to be able to access and apply this knowledge, but the knowledge must be there in the first place. Any claim that is not so, or that knowledge can always be found from other sources when it is needed, is naive (Dawson, 1993).

Shavelson, Ruiz-Primo, and Wiley (2005) present a conceptual framework for characterizing science goals and student achievement that includes declarative knowledge (knowing that, domain-specific content: facts, definitions and descriptions), procedural knowledge (knowing how, production rules/sequences), schematic knowledge (knowing why, principles/schemes) and strategic knowledge (knowing when, where and how our knowledge applies, strategies/domain-specific heuristics). For each combination of knowledge type and characteristic (extent — how much? —, structure — how it is organized? — and others), Li and Shavelson (2001) have begun to identify assessment methods. However, while conceptually it is possible to distinguish knowledge types, in practice they are difficult to distinguish, moreover, assessment methods do not line up perfectly with knowledge types and characteristics. For example, measuring the extent of declarative knowledge, multiple--choice test and short-answer questions is cost-time efficient and very reliable. To measure the structure of declarative knowledge, concept- and cognitive-maps provide valid evidence of conceptual structure (Ruiz-Primo

& Shavelson, 1996a). To measure procedural knowledge, performance assessments are needed, not paper-and--pencil assessments (Ruiz-Primo & Shavelson, 1996b). Sadler (1998) provided evidence of the validity of multiple tests for measuring schematic knowledge. Strategic knowledge is rarely ever directly measured. Rather, it is implicated whenever other types of knowledge are accessed (Shavelson *et al.*, 2005).

Ferguson-Hessler and de Jong (1990) distinguished four major types of knowledge for the content of an adequate knowledge base with regard to its importance for problem solving:

1. Situational knowledge is knowledge about situations as they typically appear in a particular domain. Knowledge of problem situations enables the solver to sift relevant features out of the problem statement.
2. Declarative knowledge, also called conceptual knowledge, is static knowledge about facts and principles that apply within a certain domain.
3. Procedural knowledge is a type of knowledge that contains actions or manipulations that are valid within a domain. Procedural knowledge exists alongside declarative knowledge in the memory of problem solvers.
4. Strategic knowledge helps the student to organize the problem-solving process by showing the student which stages he should go through in order to reach a solution.

Later, these authors described different aspects of quality of knowledge which can occur in all types of knowledge. At stake is hierarchical organisation (superficial vs. deeply embedded), inner structure (isolated knowledge elements vs. well structured, interlinked knowledge), level of automation (declarative vs. compiled) and level of abstraction (colloquial vs. formal) (de Jong & Ferguson-Hessler, 1996).

From the Anderson's cognitive perspective, the components of knowledge needed to solve problems can be broadly grouped into factual (declarative), reasoning (procedural), and regulatory (metacognitive) knowledge/skills, and all play complementary roles (Anderson, 1980). In accordance with the work of O'Neil and Schacter (1999), to be a successful problem solver, one must know something (content knowledge), possess intellectual tricks (problem-solving strategies), be able to plan and monitor one's progress towards solving the problem (metacognition), and be motivated to perform. An article of Richard E. Mayer (1998) examines the role of cognitive, metacognitive and motivational skills in problem solving, and concludes that all three kinds of skills are required for successful problem solving in academic settings.

EFFECTS OF KNOWLEDGE TYPES ON STUDENTS SOLVING SCIENCE PROBLEMS

According to Kempa's studies (Kempa, 1991; Kempa & Nicholls, 1983), a direct connection emerges between cognitive structure (long-term memory structure) and problem-solving difficulties. These difficulties are usually attributable to one or more of the following factors:

1. The absence of knowledge elements from a student's memory structure.
2. The existence, in the student's memory structure, of wrong or inappropriate links and relationships between knowledge elements.
3. The absence of essential links between knowledge elements in the student's memory structure.
4. The presence of false or irrelevant knowledge elements in the student's memory structure.

In terms of Ausubel's theory (Ausubel *et al.*, 1978), if students are meaningfully to incorporate new knowledge into existing knowledge structure, then we would expect to see relationships between conceptual knowledge after instruction and achievement (Pendley *et al.*, 1994). Indeed, it was found that conceptual (declarative) knowledge is an excellent predictor of problem solving performance (Friege & Lind, 2006; Solaz-Portolés & Sanjosé, 2006). On the other hand, expert performance seems to lie in the organization of the experts' domain knowledge. Experts possess a large knowledge base that is organized into elaborate, integrated structures, whereas novices tend to possess less domain knowledge and a less coherent organization of it (Zajchowski & Martin, 1993). The way knowledge is organised allows optimised access to the long-term memory. The borders between long-term memory and working memory of experts become fluent so that the capacity of the working memory in comparison to a novices' memory is considerably expanded (Ericsson & Kintsch, 1995).

Research on problem solving has shown that the psychometric variable working-memory can be predictive, in certain cases, of student performance (Johnstone *et al.*, 1993; Niaz & Loggie, 1993; Tsaparlis *et al.*, 1998). A characteristic model of problem solving is the Johsnstone — El-Banna model (Johnstone & El-Banna, 1986). This model is based on working-memory theory as well as on Pascual-Leone's M-space theory. It states that a student is likely to be successful in solving a problem if the problem has a mental demand which is less than or equal to the subject's working-memory capacity, X (i.e., $Z \leq X$, the authors approximated the Z value to the number of steps in the solution of the problem for the least talented but ultimately successful students), but fail for lack of information or recall, and unsuccessful if $Z > X$, unless the student has strategies that enable him to reduce the value of Z to become less than X. Simple problems have been used to study the necessary conditions for the validity (Tsaparlis, 1998), as well as the operation and the validity itself (Tsaparlis & Angelopoulos, 2000) of the Johnstone — El-Banna model.

Two studies of Lee and co-works (Lee, 1985; Lee *et al.*, 1996) have shown that successful problem solving is related to cognitive variables: prior knowledge, concept relatedness, idea association, problem translating skill and prior problem experience. Concept relatedness is a measure of the relatedness between concepts that are involved in problem solving. Idea association measures the ability to associate ideas, concepts, words, diagrams or equations through the use of cues which occur in the statements of the problems. Problem translating skill measures the capacity to comprehend, analyse, interpret and define a given problem. Prior problem solving experience is a measure of the prior experience in solving the similar problems. In an extension of the two previous studies (Lee *et al.*, 2001), they investigate the effect of the same cognitive variables (except for prior problem solving experience) in solving other type of problems, namely from different topics and levels. The findings of these studies are consistent and link the success of problem-solving to adequate translation of problem statement and relevant linkage between problem statement and knowledge.

Friege and Lind (2006) reported that conceptual knowledge and problem scheme knowledge are excellent predictors of problem solving performance. A specific problem scheme consists of situational, procedural and conceptual knowledge combined in one. Problem schemes are a high quality type of knowledge characterised by a very profound and interlinked knowledge. A detailed analysis shows that conceptual knowledge is more typical of low achievers (novices) in problem solving whereas problem scheme knowledge is predominately used by high achievers (experts).

Camacho and Good (1989) described differences in the way experts and novices go about solving problems. Successful solvers' perceptions of the problem were characterized by careful analysis and reasoning of the task, use of related principles and concepts to justify their answers, frequent checks of consistency of answers and reasons, and better quality of procedural and strategic knowledge. Unsuccessful subjects had many knowledge gaps and misconceptions.

De Jong and Fergurson-Hessler (1986) have found that poor performers organized their knowledge in a superficial manner, whereas good performers had their knowledge organized according to problem schemata with each problem schema containing all the knowledge — declarative, procedural and situational — required for solving a certain type of problem. In a subsequent experiment (Ferguson-Hessler & de Jong, 1990), these researchers collected information on differences in study processes between students who are good problem solvers and students who are not. Good and poor performers did not differ in the number of study processes scored, indicating that both groups studied in an equally active way. They differed in the type of processes scored: good students applied more deep processing and less superficial processing than poor students. Poor performers were found to pay more attention to declarative knowledge, whereas good performers tended to pay attention to procedural and situational knowledge.

Today, more and more researchers pay attention to the notion of metacognition, the management of one's own cognitive behaviour. Several studies have investigated the relationship between metacognitive abilities and academic achievement (Leal, 1987; Pintrich & DeGroot, 1990; Pokay & Blumendeld, 1990). One limitation in these investigations is that they relied on self reports of students to assess metacognitive strategies they use. The study of Otero, Campanario and Hopkins (1992) develops an instrument for measuring metacognitive comprehension monitoring ability (CMA) that does not rely entirely on subjects' self-reports. Their results indicated that CMA was significantly related to academic achievement, as measured by marks. In Horak's paper (1990), interactions were noted between the students' cognitive style (field-dependence/independence) and their use of problem-solving heuristics and metacognitive processes.

The results of the work of Artz and Armour-Thomas (1992) suggest the importance of metacognitive processes in mathematical problem solving in a small-group setting. A continuous interplay of cognitive and metacognitive behaviours appears to be necessary for successful problem solving and maximum student involvement. In the same way, the study of Teong (2003) demonstrates the effect of metacognitive training on mathematical word-problem solving. Experimental students, who developed the ability to ascertain when to make metacognitive decisions and elicit these decisions, outperformed control students on cleverness to solve word-problems. An experimental and interview-based design was used by Longo, Anderson and Wicht (2002) to test the efficacy of a new generation of knowledge representation and metacognitive learning strategies called visual thinking networking (VTN). Students who used the VTN strategies had a significantly higher mean gain score on the problem solving criterion test items than students who used the writing strategy for learning science. To get an overview of the characteristics of good and innovative problem-solving teaching strategies, Taconis, Fergusson-Hessler and Broekkamp (2001) performed an analysis of a number of articles published between 1985 and 1995 in high-standard international journals, describing experimental research into the effectiveness of a wide variety of teaching strategies for science problem solving. As for learning conditions, both providing learners with guidelines and criteria they can use in judging their own problem-solving process and products, and providing immediate feedback to them were found to be important prerequisites for the acquisition of problem-solving skills. Abdullah (2006) indicated that there are only a few studies looking specifically into the role of metacognitive skills in physics in spite of the fact these skills appear to be relevant in problem solving. This researcher has investigated the patterns of physics problem-solving through the lens of metacognition.

DIRECTIONS FOR PRACTICE

Skill in problem solving depends on the effective interaction of knowledge types such as those discussed above. Based on the overview on problem solving presented in this paper, a number of instructional measures that will assist teachers are suggested below.

1. A conceptual understanding of the topic must be obtained before students are given problems to solve, rather than trying to get this understanding by means of problem solving. A valuable science education will integrate the process of acquiring and applying conceptual knowledge. One technique that can be used by teachers to help students organise their understanding of a topic is concept mapping (Pendley *et al.*, 1994). The introduction of a concept map can often assist students to understand the concepts and the relationships between them (Novak & Gowin, 1984).
2. In instructional texts, declarative knowledge dominates, whereas procedural and situational knowledge is more implicit and has to be extracted, often by deep processing. Stimulating specific, deep study processes (e.g., explicating, relating, and confronting) might encourage students to change their learning habits (Ferguson-Hessler & de Jong, 1990).
3. Traditional methods and instructional strategies of teaching science are not compatible with attaining conceptual learning and higher-order cognitive skills (Zoller *et al.*, 1995). A major purpose of science education should be to develop instructional practices for developing scientific reasoning skills: laboratory work, inquiry-based science, computer simulations, analyze data quantitatively, construct explanations, and critical thinking and decision-making capacity. Improvement in reasoning skills has been shown to occur as a result of prolonged instruction and can lead to long-term gains in science achievement (Shayer & Adey, 1993).
4. Encourage qualitative understanding of problems, rather than just giving numerical procedures (Neto & Valente, 1997). Begin by questions that may be text-based or diagrammatic and require to invoke underlying concepts of the basic theories of science in order to answer the question. Qualitative discussions could be carried out while problems are solved on the chalkboard, and also by getting students to work together while solving problems, with students being asked to derive general procedures rather than mathematical solutions.
5. Provide students with diverse, continual and prolonged problem-solving experiences. Associated with all problems there are three variables: the data provided, the method to be used and the goal to be reached (Johnstone, 1993). Once students have derived and understood procedures for basic problems (recall of algorithms), they should be given plenty of practice in other problem types, for example, problems unfamiliar to the student, which for their solution, in addition to conceptual knowledge application, also require analysis, and synthesis capabilities, as well as making connections and evaluative thinking. Give practice of similar problem solving strategies across multiple contexts to encourage generalization.
6. Offer measures in the field of metacognition, such as teaching the existence of functional knowledge types and the role of problem schemata. Use problem-solving heuristics and metacognitive activities. Explain the role of metacognitive skills in problem-solving steps. Metacognitive skills can be found in the steps of planning, reflecting (monitoring progress), checking (verifying results), and interpreting problem-solving (Abdullah, 2006).
7. It is useful for teachers to know that you can change the M-demand (mental demand) of an item (problem) without changing its logical structure. Thus they can promote student success by decreasing the amount of information required for processing, that is, avoiding working memory overload (Níaz, 1987). Johnstone, Hogg, and Ziane (1993) give evidence that a physics problem can be presented in such a way as to reduce the noise input to the processing system, and as consequence to allow greater success for all students but particularly for the field-dependent students. According to these authors the form of a problem with words plus a diagram can be seen as a way of reducing memory overload.
8. By providing goal-free problems to students, Sweller, van Merrienboer, and Paas (1998) argued that students only had to maintain the problem state and any problem-solving step applicable to that state and thus reduced the cognitive load. These same authors corroborated that providing worked examples was shown to be another effective way to decrease extraneous cognitive load. Worked examples with annotations about their crucial features were found to be helpful for students in applying schemas in problem-solving (Cooper & Sweller, 1987).

9. Using external representations through symbols and objects to illustrate a learner's knowledge and the structure of that knowledge can facilitate complex cognitive processing during problem-solving (Solaz-Portolés & Sanjosé, 2007). Such external representations can help a learner elaborate the problem statement, transform its ambiguous status to an explicit condition, constrain unnecessary cognitive work, and create possible solutions (Scaife & Rogers, 1996). Larkin (1989) argued that an external representation supports human problem-solving by reducing the complexity of problem and its associated mental workload. Moreover, Bauer and Johnson-Laird (1993) showed that diagrams helped learners solve a problem more effectively and efficiently.

Two methodologies of instruction that have demonstrated their efficacy on problem-solving ability are the Problem Solving Heuristic (Lorenzo, 2005) and the Modeling Method (Malone, 2006). The Problem Solving Heuristic intends to help students to understand the steps involved in problem solving (metacognitive tool), and provide them with an organized approach to tackling problems in a systematic way. This approach guides students by means of logical reasoning to make a qualitative representation of the solution of a problem before undertaking calculations, using a *backwards strategy*, which thus comprises a cognitive tool. Possible applications of heuristics in the classroom include its use in formative assessment, to identify and to overcome student alternative conceptions, problem-solving in a cooperative environment, and to reduce the gender gap in science. The success of the Modeling Method is the structuring of physics knowledge so that it is no longer a list of equations to memorize but a coherent body of knowledge organized into a number of models. The models contain a number of distinct representations that allow the students to flexibly apply their knowledge in a variety of situations and to check internal coherence in the models developed. For example, students have both algebraic and graphical representations chunked with each model which can allow for more flexibility during problem solving. The internal coherence of the models developed is tested whenever students demonstrate that the same prediction occurs no matter what representation utilized.

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