Cognitive variables in science problem solving: A review of research

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This paper provides an overview of research into cognitive variables that are involved in problem solving and how these variables affect the performance of problem solvers. The variables discussed are grouped together in: prior knowledge, formal reasoning ability and neo-Piagetian variables, long-term memory and working memory, knowledge base, and metacognitive variables.

Introduction.

During the 1960s and 70s, researchers develop general problem-solving models to explain problem-solving processes (Bransford and Stein, 1984; Newell and Simon, 1972; Polya, 1957). The assumption was made that by learning abstract (decontextualized) problem solving skills, one could transfer these skills to any situation. Under the influence of cognitive learning theories, the last 25 years have seen a great deal of work in the study of problem solving and there is a growing consensus about the kinds of mental processes involved and the kinds of difficulties problem solvers have. Today we know problem solving includes a complex set of cognitive, behavioural, and attitudinal components. Mayer and Wittrock (1996) defined problem solving as a cognitive process directed at achieving a goal when a solution method is not obvious to the problem solver. Palumbo (1990) supports problem solving as a situational and context-bound process that depends on the deep structures of knowledge and experience. Garofalo and Lester (1985) indicated that problem solving includes higher order thinking skills such as visualization, association, abstraction, comprehension, manipulation, reasoning, analysis, synthesis, generalization, each needing to be managed and coordinated.

In the realm of cognitive psychology, problem solving has a dual identity as a basic cognitive function and also an activity of educational importance (Elshout, 1987). In a matrix with rows representing basic cognitive functions and columns representing important educational activities, Elshout showed that problem solving, as a basic cognitive function, is involved in all educational activities and as an activity, involves all the basic cognitive functions.

Problem solving plays a crucial role in the science curriculum and instruction in most countries (Gabel and Bunce, 1994; Heyworth, 1999; Lorenzo, 2005). It is a much-lamented fact that students often do not succeed in applying knowledge that they have acquired in lessons at school or in everyday contexts. This circumstance seems to apply especially to science lessons (Friege and Lind, 2006). As a consequence, improving students' problem-solving skills continues to be a major goal of science teachers and science education researchers. In order to achieve the ability to solve problems in science, there are two concerns (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. Modeling Instruction has demonstrated its efficacy in improving students' ability to solve problems (Malone, 2006). This author attempts to explain why modeling pedagogy might help students become more superior problem solvers by means of a review of the pertinent literature investigating the differences in problem-solving and knowledge structure organization between experts and novices. Evidence from the research literature suggests that a variety of cognitive factors is responsible for science problem-solving performance.

The purpose of this paper is to present an overview of a number of cognitive variables involved in problem solving in science and how these factors mediate the performance of problem solvers. The variables discussed are grouped together in: prior knowledge, formal reasoning ability and neo-Piagetian variables (mental capacity, field-dependence/field-independence, mobility/fixity dimension, and convergent/divergent characteristic), long-term memory (LTM) and working memory (WM), knowledge base, and metacognitive variables. This exposition could suggest some directions for classroom instruction to facilitate more effective problem solving.

Prior knowledge.

According to Ausubel's theory, if students are meaningfully to incorporate new knowledge into existing knowledge structure, then the existing structure is an important factor in what they learn (Ausubel et al., 1978). In the psychology of Ausubel, that lays great stress upon the internal mental networks that a student develops for himself rather than upon external teaching networks. In this is the implicit idea that every student constructs his own knowledge in his own way. To learn, the student has to *unpack* what he is taught and then *repack* it in a way that suits his previous knowledge and his own learning style. The central idea in Ausubel's assimilation theory is that of meaningful learning, which defines as nonarbitrary, substantive, nonverbatim incorporation of new knowledge into cognitive structure. Cognitive structure is the framework stored in our minds that grows and develops from chilhood to senescence. Ausubel's concept of meaningful verbal learning which has gained wide currency stresses the importance of prior knowledge as the most important factor influencing learning (Novak, 1980). Emphasis is placed on the comprehension of concepts and the inter-relations among concepts; as links between prior knowledge and new knowledge are established, meaningful learning is said to occur. The implication is that students with the appropriate prior knowledge will be able to comprehend more and achieve better.

In terms of this theory, we would expect to see relationships between prior knowledge and post knowledge and achievement. Entwistle and Ramsdem (1983) have shown that the level of students' prior knowledge and factors associated with course and teaching affect the way students approach their studies and subsequently what they learn. They found that prior knowledge was a particular concern in the sciences.

Concepts maps can be constructed to examine students' starting points before instruction. The maps will do more than identify the range of concepts and ideas that students hold before instruction; they will also reveal the students' alternate conceptions (Ebenezer, 1992). Hegarty-Hazel and Prosser (1991) have used concept-mapping tasks as a way of obtaining information about how students see the structural relationships between the major concepts included in the topic they are studying. The tasks used in this study asked students to describe briefly the relationship between concepts included in a list that had been previously identified from a analysis of the curriculum.

Much of the published work in science education has focused on the relation between prior knowledge and post knowledge, and the difficulties in changing and developing students' conceptions. Several studies shows that prior knowledge is statistically significantly related to variation in science achievement (Lee et al., 2001; Chandran et al., 1987; Hussein, 1989; Lawson, 1983; Solaz-Portolés and Sanjosé, 2006). They indicate that prior knowledge is good predictor of problem-solving performance.

Formal reasoning ability and neo-Piagetian variables.

Piaget taught us that young children are fundamentally different kinds of thinkers and learners from adults –that they think in concrete terms, cannot represent concepts with structure of scientific concepts, are limited in their inferential apparatus, and so forth. His stage theory described several general reorganizations of the child's conceptual machinery –the shift from sensorimotor to representational thought, from pre-logical to early concrete logical thought, and finally to the formal thinking of adults. In Piaget's system, these shifts are domain independent (Carey, 1986). Developmental level is a Piagetian concept and refers to the ability of the subject to use formal reasoning (Lawson, 1985). Psychological tests are research tools used more often to determine students' level of reasoning and neo-Piagetian variables.

Most of the discussion of Piaget's work among science educators has focused on the transition between the concrete operational and formal operational stages and ways in which instruction can be revised in light of this model (Bodner, 1986). A great deal of attention has been given to the work of Piaget, pointing out that there may be a connection between age (maturity) and the complexity of thinking of which a learner is capable. Thus, Piaget's followers (Herron, 1978; Lawson and Karplus, 1977) argue that students who have not attained formal operational ability will not be able to comprehend meaningfully abstract concepts and principles of science.

The neo-Piagetian theory of Pascual-Leone argues that formal reasoning alone cannot explain student success, and provides explanatory constructs for cognitive development by postulating: a) the M-operator or M-space, which accounts for an increase in students' information processing capacity with age (Pascual-Leone and Goodman, 1979); b) the field factor (field-dependence/field -independence), which represents the ability of a subject to disembed information in a variety of complex and potentially misleading instructional context, thus, the learners who have more difficulty than others in separating *signal* from *noise* are classed as field-dependent (Pascual-Leone, 1989); and c) the mobile/fixed cognitive style, that arises from a combination of mental capacity (M-space) and disembedding ability, fixity characterizes consistency of function of field-independent subjects in a field-independent fashion, while mobility provides for variation according to circumstances (Pascual-Leone, 1989).

Positive linear relationships between formal reasoning activity (developmental level) and achievement in science problem-solving have been described by a number of authors (Lawson, 1983; Chandran et al., 1987; Níaz, 1987a; Hussein, 1989; Bunce and Huchinson, 1993; Tsaparlis et al., 1998, Demerouti et al., 2004). More general studies by Staver and Halsted (1985) and by Robinson and Níaz (1991) also support this relationship.

In science, mental capacity (M-space) is associated with students' ability to deal with problem-solving (Níaz, 1987a; Tsaparlis, Kousathana and Níaz, 1998; Tsaparlis, 2005). However, students with higher information processing capabilities (higher mental capacity scores) do not always perform better than students with lower mental capacity scores (Chandran et al., 1987; Robinson and Níaz, 1991).

Studies by Níaz (1987), Tsaparlis (2005), Danili and Reid (2006), Tsaparlis, Kousathana and Níaz (1998), Johnstone, Hogg and Ziane (1993), and by Demerouti, Kousathana and Tsaparlis (2004) have indicated that students with better disembedding ability (i.e. field-independent students) are more successful solving problems than students with lower disembedding ability scores (i.e. field-dependent students). However, studies by Chandran, Treagust and Tobin (1987), and by Robinson and Níaz (1991) have shown that this cognitive variable played no significant role in science achievement. Overall, the field dependent/independent test is considered by some researchers a very powerful instrument to predict academic performance of individuals (Tinajero and Paramo, 1998).

The results of various works (Níaz, 1987b; Níaz et al., 2000; Stamovlasis et al., 2002) support the hypothesis that mobility-fixity dimension can serve as a predictor variable of students' performance in problem solving. Moreover, the most *mobile* students performed best on creativity tests whereas *fixed* students performed better on tests of formal reasoning (Níaz and Nuñez, 1991). Mobile subjects are those who have available to them a developmentally advanced mode of functioning (i.e., field-independence) and a developmentally earlier mode (i.e., field-dependence)(Níaz, 1987b).

Many researchers tended to equate divergent thinking with creativity and convergent thinking with intelligence. This has caused a great deal of controversy, with different research supporting different results (Bennett, 1973; Runco, 1986; Fryer, 1996). According to Hudson (1966), the *converger* is the student who is substantially better at intelligence test than he is at the open-ended tests; the *diverger* is the reverse. Convergent thinking demands close reasoning; divergent thinking demands fluency and flexibility (Child and Smithers, 1973). In the literature little research is reported on convergent/divergent cognitive styles and performance in science. In the work of Danili and Reid (2006) the convergent/divergent characteristic correlated with pupils' performance in assessment where language was an important factor, but not in algorithmic types of questions or in questions where there is a greater use of symbols and less use of words. In almost all the tests the divergent pupils outperformed convergent pupils and, when there were short answer or open-ended questions, the differences in the performance between the divergent and convergent groups became larger.

Long-term memory (LTM) and working memory (WM).

Information processing theory focuses on learning and learner and suggests mechanisms in the learning process (Osborne, 1985). This theory enables us to understand the learning limitations and, more important, to help the students to circumvent the problems. In terms of this theory, long-term memory (LTM) helps us to select the important from the unimportant. If we decide to act on this information, it is encoded for storage or translated into a response. The storage process is most efficient if we link the new information to something already in the LTM. The LTM seems to have almost infinite capacity for holding information, but the retrieval system is not always efficient. The more similarities and anchorages we can find for attaching the new information, the more easily it will be retrieved. The short-term memory (STM), sometimes also referred to as working memory (WM), is the space where the information derived from the LTM and from outside is brought together in mental operations and transformations. It is here where new and recalled information interacts, is linked and sequenced for a response (to learning task or problems) or for storage (Johnstone, 1993; Kempa, 1991). It is well established through psychological research that the capacity of our working memory is rather limited. Most people can hold only about 7 ± 2 information units (chunks) in their working memory. What constitutes a information unit or chunk in this space is controlled by our previous knowledge, experience and acquired skills (Johnstone and El-Banna, 1986). Thus, the size of each unit of information depends upon the way it is perceived by the person (Johnstone, 1983). Figure 1 shows one version of the information processing theory in a schematic form.

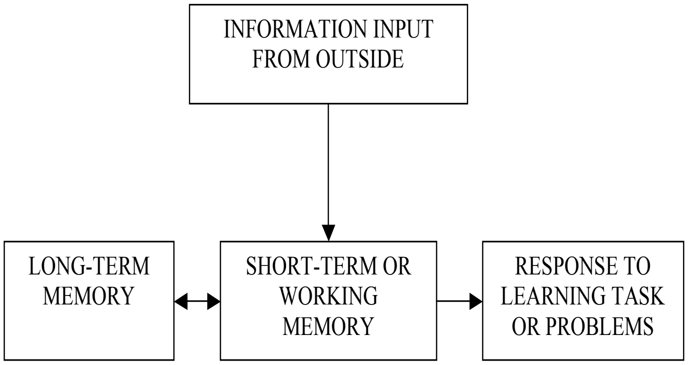

Figure 1. *Schematic representation of the information processing theory.*

In science education, cognitive structure is commonly defined as the representation of relations between elements of LTM. Cognitive psychologists posit *the essence of knowledge is structure* (Anderson, 1984, p.5). Research on the cognitive aspects of science learning has provided evidence that professional scientists and successful students develop elaborate, well differentiated, and highly integrated frameworks of related concepts (Shavelson et al., 2005) to form a static network (Hendry and King, 1994). This *static* knowledge about facts, concepts and principles (in the LTM) is called declarative or conceptual knowledge (Fergusson-Hesler and de Jong, 1990). Declarative knowledge is characterized by what people can report (knowing that) and facilitates the construction of organized frameworks of science concepts while providing scaffolding for the acquisition of new concepts (Novak and Gowin, 1984).

According to Kempa's studies (Kempa, 1991; Kempa and Nicholls, 1983), a direct connection emerges between cognitive structure (LTM 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, 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 a excellent predictor of problem-solving performance (Friege and Lind, 2006; Solaz-Portolés and Sanjosé, 2006). On the other hand, expert performance seems to reside 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 and 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 and 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 and Loggie, 1993; Tsaparlis et al., 1998). A characteristic model of problem solving is the Johnstone–El Banna model (Johnstone and 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 and Angelopoulos, 2000) of the Johnstone–El Banna model.

Knowledge base.

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 and Palacio-Cayetano, 2003). The development of a knowledge base is important both in terms of its extent and its structural organization. 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 others 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/mentals models) 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 we can conceptually distinguish knowledge types, in practice they are difficult to distinguish and assessment methods do not line up perfectly with knowledge types and characteristics. For example, to measure the extent of declarative knowledge, multiple-choice test and short-answer questions are 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 and Shavelson, 1996a). To measure procedural knowledge, performance assessments, not paper-and-pencil assessments, are needed (Ruiz-Primo and Shavelson, 1996b). Sadler (1998) provided evidence of the validity of multiple tests for measuring schematic knowledge (mental models). 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 that can occur in all types of knowledge. Aspects of quality of knowledge are hierarchical organization (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 and Ferguson-Hessler, 1996) .

Two studies of Lee and co-works (Lee, 1985; Lee et al., 1996) have shown that successful problem solving is related to cognitive variables: 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 investigated the effect of the same cognitive variables (except for prior problem solving experience) in solving other type of problems, such as the 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 into one. Problem schemes are a high quality type of knowledge characterised by a very profound and interlinked knowledge. A detailed analysis shows that the conceptual knowledge is more typical for low achievers (novices) in problem solving whereas the 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 and de Jong (1990) collected information about 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.

Metacognitive variables.

A classical definition of metacognition is that offered by Flavell (1976, p.232): *Metacognition refers to one's knowledge concerning one's own cognitive processes and products or anything related to them, e.g., the learning-relevant properties of information or data.* 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 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.

Several studies have investigated the relationship between metacognitive abilities and academic achievement (Leal, 1987; Pintrich and DeGroot, 1990; Pokay and Blumenfeld, 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) develop 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 achievement academic, as measured by marks. In the paper of Horak (1990) were noted interactions 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 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 making metacognitive decisions and elicit these decisions, outperformed control students on cleverness to solve word-problems. And 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 the 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.

Summary and conclusion.

In accordance with the results of the investigations that we have analysed, success in problem solving appears to be influenced by the following cognitive variables:

- Prior knowledge.
- Formal reasoning activity (developmental level).
- Mental capacity (M-space).
- Disembedding ability (field dependent/independent).
- Mobility-fixity dimension.
- Divergent-convergent thinking.
- Declarative knowledge (conceptual knowledge).
- Working memory capacity.
- Concept relatedness.
- Idea association.
- Problem translating skill.
- Prior problem solving experience.
- Procedural knowledge.
- Strategic knowledge.
- Problem scheme knowledge (problem schema containing all the knowledge required for solving a problem).
- Metacognitive skills.

Obviously, skill in problem solving depends on the effective interaction of cognitive variables as those discussed above. In order to improve problem-solving skills, the standard approach is to look at the cognitive variables and processes involved in skilled problem-solving performance and then to derive instructional approaches that will assist students. In this paper, we are presented cognitive variables involved in the solving of problems. In a later article we will address cognitive processes in problem solving.

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