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WORKING MEMORY IN SCIENCE PROBLEM SOLVING: A REVIEW OF RESEARCH

MEMORIA DE TRABAJO EN LA RESOLUCIÓN DE PROBLEMAS DE CIENCIAS: UNA REVISIÓN DE INVESTIGACIONES

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Abstract: The aim of this review is to present the case that working memory makes a vital contribution to problem solving. Following a brief introduction to working memory, links between working memory and cognitive tasks including problem solving are reviewed and illustrated. Next, relationships between mental representations of the problem (mental models) that are created in working memory and problem solving performance are described. Finally, applications of research for classroom practice is considered; this includes four main approaches to deal with the limit of working memory capacity to help students solve problems: to possess a large knowledge base, to decrease the information load in problem solving, to increase students' working memory capacity through specialized training programs, and to use representations.

Key words: problem-solving, working memory, cognitive tasks, mental models, instructional approaches

Resumen: Con esta revisión se pretende poner de manifiesto la importancia de la memoria de trabajo en la resolución de problemas. A partir de una breve introducción a la memoria de trabajo, se analizan e ilustran las conexiones entre memoria de trabajo y tareas cognitivas, incluyendo en ellas la resolución de problemas. A continuación, se describen las relaciones entre las representaciones mentales del problema (modelos mentales), que se generan en la memoria de trabajo, y la resolución de problemas. Finalmente, se ofrecen aplicaciones prácticas de la investigación para uso en el aula. Estas aplicaciones incluyen cuatro puntos para abordar las limitaciones de la memoria de trabajo en la resolución de problemas: poseer una gran base de conocimiento, decrecer la carga informativa en los problemas, incrementar la memoria de trabajo mediante programas de entrenamiento específicos, y usar representaciones.

Palabras clave: resolución de problemas, memoria de trabajo, modelos mentales, tareas cognitivas, enfoques instruccionales

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 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.

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). In order to achieve the ability to solve problems in science, there are two issues (Lee, Tang, Goh & Chia, 2001): developing problem solving skills in students through science education, and looking at the difficulties faced by students in this area and finding ways to help them overcome these difficulties.

Recently, the types of knowledge needed to solve problems in science and some directions for classroom instruction to facilitate more effective problem solving have been reported (Solaz-Portolés & Sanjosé, 2008). An overview of research (Solaz-Portolés & Sanjosé, 2007a) into cognitive variables that are involved in problem solving and how these variables mediate the performance of problem solvers points to a strong connection between working memory and problem solving. The present study focuses on working memory and how this memory affects problem solving.

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The purpose of this paper is fourfold: *a)* to present a brief introduction to working memory; *b)* to show links between working memory and cognitive tasks including problem solving, and between working memory and mental representations of the problem (mental models); *c)* to emphasize relationships between mental models and success in problem solving; and *d)* to suggest some directions for classroom instruction to facilitate more effective problem solving.

WHAT IS WORKING MEMORY?

Eleven different models for working memory have been described (Miyake & Shah, 1999). The best known and most widely cited model of working memory is Baddeley's model. Baddeley (1995) has described three main kinds of memory: short-term, long-term, and working. Short-term has a half-life of about fifteen seconds and holds about seven *chunks* of information. These *chunks* can consist of any information that one can think of as a unit, e.g., words, patterns of chess pieces, or the Pythagorean theorem. The rest of memory is called long-term. It has a very large capacity, but one is not aware of its contents and these are not directly available for reasoning. Parts of the contents of long-term memory can be brought into short-term memory, i.e., activated. Finally, working memory consists of short-term memory plus reasoning and control mechanisms that swap information between short-term and long-term memory. Thus, working memory is the set of mechanisms used in human cognition for retrieving, manipulating, and maintaining information during processing (Baddeley, 1986, 1990).

Baddeley (2002) proposed that working memory was composed of a phonological loop, a visuospatial sketchpad, an episodic buffer, and the central executive. The phonological loop is responsible for temporary storage and manipulation of acoustic and verbal information. The visuospatial sketchpad is used to temporally store and process visual and spatial information, such as shapes, locations, or movements. The episodic buffer is viewed as an interface that assembles information from working memory and long-term memory. The central executive is responsible for allocating attention and coordinating activities between the three other components. The ideas of phonological and visuospatial working memory are widely supported by other working memory models (Barnard, 1999; Oberauer, Süb, Schulze, Wilheim, & Wittmann, 2000).

Working memory models have evolved from a single unitary memory store to a system containing multiple cognitive subsystems responsible for different storage and executive control functions. For example, Miller's (1956) finding that immediate memory stored only 7 ± 2 *chunks* of information represented the early understanding of working memory as a single information store. Although researchers differ in their specifications of working memory subsystems, most agree that working memory is responsible for storing task-relevant information while performing cognitive tasks, coordinating information processing tasks, and inhibiting interference from activated task-irrelevant information (Miyake & Shah, 1999).

Working memory has storage function and researchers use working memory capacity to represent the amount of information activated and retained while completing cognitive tasks (Yuan, Steedle, Shavelson, Alonzo & Pezzo, 2006). The capacity of working memory is limited, and the imposition of either excess storage or processing demands in the course of an on-going cognitive activity will lead to catastrophic loss of information from this temporary memory system. For the model developed by Brooks and Shell (2006) (Interactive Compensatory of Learning Model), *expertise* is thought of in terms of forming ever-larger knowledge *chunks*, and *ability* is related strongly to working memory capacity.

A majority of researchers agree that long-term memory is a source of information for working memory (Engle, Kane & Tuholski, 1999; Ericsson & Delaney, 1999). However, sensory information from the external world must also be an important part of the content of working memory (Kyllonen & Christal, 1990). Thus, both long-term memory and the external world are sources of working memory content.

RESEARCH ON WORKING MEMORY AND COGNITIVE TASKS

In studies of working memory, a wide variety of tools is used to measure working memory. For example, Yuan et al. (2006) contrast several commonly used measures of working memory, including simple memory span, dual-tasks, and other measures used in prior studies. Engle (1994) reported that an individual's working memory capacity (as measured by performance on a specially designed task) correlates well with performance on a variety of other tasks. Engle interprets this correlation as evidence that all of these tasks require use of a common resource, the individual's working memory, which influences performance.

Holzman, Pellegrino and Glaser (1982) have claimed that a major source of individual differences on reasoning tasks lies in how much information one must maintain in working memory, especially while effecting some transformation. Kyllonen and Christal (1990) found that latent variables for reasoning ability and working memory correlated approximately $r = 0.8$ in four large studies. These authors noted that most performance processes (such as encoding and inference) and executive processes (such as goal setting, goal management, and monitoring) in information processing models of reasoning are presumed to occur in working memory.

The impact of working memory on academic achievement is considerable. Between the ages of 7 and 14 years, children who score poorly on working memory measures linked with executive skills typically perform below expected standards in national curriculum assessments of science in England (Gathercole, Brown & Pickering, 2003).

Miyake et al. (2000) identified three executive functions in working memory: shifting, updating, and inhibition. Shifting involves moving backwards and forwards between multiple tasks, operations, or mental sets. Updating requires monitoring and coding of incoming information and appropriately revising the items held in working memory by replacing no-longer-relevant information with new, more relevant information. Inhibition refers to the ability to deliberately inhibit dominant, automatic, or prepotent responses. In the study of St Clair-Thompson and Gathercole (2006), scholastic attainment, shifting, updating, inhibition, and verbal and visuo-spatial working memory were assessed in 11- and 12-year old children. Inhibition was associated with achievement in mathematics and science, and domain-specific associations existed between visuo-spatial working memory and attainment in mathematics and science.

But, why does working memory constrain cognitive processes? One suggestion is that working memory provides a resource for the individual to integrate knowledge recovered from long-term memory with information in temporary storage (Swanson & Saez, 2003). A child with weak working memory capacities is therefore limited in their ability to perform this operation in important classroom-based activities. A related suggestion is that poor working memory skills result in pervasive learning difficulties because this system acts as a bottleneck for learning in many of the individual learning episodes required to increment the acquisition of knowledge (Gathercole, 2004).

WORKING MEMORY AND SCIENCE PROBLEM SOLVING

Working memory capacity plays an important role in many different types of problem solving (Welsh , Satterlee-Cartmell & Stine, 1999). The ability to maintain information in a highly activated state via controlled attention may be important for integrating information from successive problem-solving steps. Working memory capacity may also be involved in a number of neo-Piagetian cognitive variables which are/work as predictors of achievement in science, including: *a)* the M-operator or M-space, which accounts for an increase in students' information processing capacity with age (Pascual-Leone & 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 that 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, which 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).

Research on problem solving has shown that the psychometric variable working memory can be predictive, in certain cases, of student performance (Johnstone, Hogg & Ziane, 1993; Níaz & Loggie, 1993; Tsaparlis, Kousathana & Níaz, 1998). A characteristic model of problem solving is the Johnstone-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, Z, 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). If Z > X, he/she will not succeed unless the student has strategies that enable him/her 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 Johnstone-El-Banna model.

Studies on the association between limited working memory capacity and information load in problem-solving provided support for the positive relationship between working memory and science achievement. Because working memory capacity limits the amount of information which can be concurrently processed, performance on science problem-solving tasks is expected to drop when the information load exceeds students' working memory capacity (Johnstone & El-Banna, 1986). Opdenacker et al.'s (1990) study reported that students gradually decreased their chemistry problem-solving performances when the amount of information to be processed exceed their working memory capacity. This fact is also consistent with Sweller's (1994) cognitive overload theory, which posits that learning processes will be negatively affected if the cognitive load exceeds the limit of working memory capacity.

In science, mental capacity (M-space) is associated with students' ability to deal with problem-solving (Níaz, 1987a; Tsaparlis et al. 1998). Gathercole, Pickering, Knight, and Stegmann (2004) found a strong relationship between working memory capacity and science achievement: the correlation coefficients between working memory measure and science achievement ranged from 0.32 to 0.5. Danili and Reid (2004) found that students with high and low working memory capacity differed significantly in their performance on chemistry tests. Tsaparlis (2005) examined the correlation between working memory capacity and performance on chemistry problem-solving and the correlations ranged between 0.28 and 0.74. However, other studies show that students with higher information processing capabilities (higher mental capacity scores) do not always perform better than students with lower mental capacity scores (Chandran, Treagust & Tobin, 1987; Robinson & Níaz, 1991).

Studies by Níaz (1987a), Tsaparlis (2005), Danili and Reid (2006), Tsaparlis et al. (1998), Johnstone et al. (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 et al. (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 as a very powerful instrument to predict academic performance of individuals (Tinajero & Paramo, 1998).

The results of various works (Níaz, 1987b; Níaz, Saud de Nunez, & Ruiz de Pineda, 2000; Stamovlasis, Kousathana, Angelopoulos, Tsaparlis, & Níaz, 2002) support the hypothesis that mobility-fixity dimension can serve as a predictor variable of students' performance on problem-solving. Moreover, the most *mobile* students performed best on creativity tests whereas *fixed* students performed better on tests of formal reasoning (Níaz & Saud de Nunez, 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).

One possibility that working memory capacity is involved in problem solving difficulties stems from the view that working memory capacity represents the capability for controlled attention, which is responsible for not only maintenance of information in highly activated state, but also for suppression or inhibition of irrelevant or misleading information. More generally, inhibitory functions of working memory capacity may be critical for what Frensch and Sternberg (1989, p.163) termed flexibility in thinking: "the ability to change one's mode or direction of thinking as a function of changing task or situational constraints".

On the other hand, individuals who are good at solving *insight* problems (*insight* problems tend to be ill-defined, that is, there is some ambiguity about problem requires, or what form the solution will take) are also good at working memory storage and processing, as measured by digit span and sentence span tasks (Murray & Byrne, 2005). Most researchers accept *insight* is subjectively different from trial-and-error or algorithmic problem-solving. Representational change theory proposes that *insight* occurs when the solver reinterprets or re-presents the problem by relaxing self-imposed constraints and/or decomposes chunked items in the problem (Knoblich, Ohlsson, Haider & Rhenius, 1999). Solving *insight* problems may require individuals to keep in mind several alternative possibilities (Murray & Byrne, 2005) and may exceed working memory capacity (Johnson-Laird & Byrne, 2002).

MENTAL MODELS AND SCIENCE PROBLEM SOLVING

According to the cognitive psychologist Mayer (1992), the process of solving problems has two steps: problem representation and problem solution. For problem representation, a learner needs to transform a problem's description to his o her internal mental representation in two stages: problem translation and integration. Problem translation extracts concepts from the textual description of the problem by using linguistic and semantic knowledge. Linguistic knowledge is used to comprehend the words' meanings in the textual description, while semantic knowledge means factual knowledge in the world. Problem integration requires a learner to connect sentences in a problems' description and produce a coherent representation. At this stage, schematic knowledge of problem classification is needed to integrate the pieces of information provided by the problem. Moreover, schematic knowledge allows a learner to determine the category of a problem. After the problem's description is translated into the learner's internal mental representation (mental model), it means that the learner has already comprehended the problem.

Pribul and Bodner (1987) concluded that the preliminary stages in the problem-solving process that involved disembedding relevant information from the statement of the problem and restructuring or transforming the problem into one the individual understands are particularly important in determining the success or failure of problem-solving process. Bodner and Domin (2000) suggest that an essential component of an individual's problem solving behaviour is the construction of a mental representation (mental model) of the problem that can contain elements of more than one representation system. The first representation establishes a context for understanding the statement of the problem. In some cases, this representation contains enough information to both provide a context for the problem and to generate a solution to the problem. In other cases, additional representations may be needed. They also found that successful problem solvers construct significantly more representations while solving a problem than those who are not successful.

One of the most influential theories to be formulated in cognitive psychology in recent years is Johnson-Laird's (1983; 2000) theory of mental models. The theory seeks to provide a general explanation of human thought; at its core is the assertion that humans represent the world they are interacting with through mental models. In order to understand a real-world phenomenon, a person has to hold what Johnson-Laird describes as a working model of the phenomenon in his or her mind. Johnson-Laird has formulated his mental model definition in his attempt to explain the reasoning processes in tasks of syllogisms and language comprehension. The author proposes that reasoning about a problem is facilitated if a person utilises a mental model that represents the relevant information in an appropriate fashion for the problem to be solved.

This theory is based on three main assumptions (Johnson-Laird, 2000):

- Each mental model represents a possibility. Models can represent relationships among three-dimensional entities or abstract entities; they can be static or kinematic. They underlie visual images, though many components of models are not visualizable.
- A mental model is iconic, that is, its parts correspond to the parts of what represents, and its structure corresponds to the structure of the possibility. The iconic nature of the model yields a conclusion over and above the propositions used in constructing the model.
- Mental models represent what is true according to the premises, but by default not what is false.

Johnson-Laird's mental model theory proposes a semantic, non-rule-based approach reasoning. According to mental model theory, human deduction depends on the construction and manipulation of analogical models in the mind. Model building and manipulation are processes that people carry out on line. Thus, models are not retrieved from long-term memory as rules or schemas are. To execute cognitive tasks, a person forms a mental representation in working memory, combining the information stored in long-term memory with the information on the task characteristics extracted by perceptual processes (Cañas, Antolí & Quesada, 2001). Reasoning capacity limitations are explained within this theory as a consequence of the limitations in the human processing capacity. The limited capacity of working memory would restrict the number of possible models considered (Santamaría, García-Madruga & Carretero, 1996). For this theory, the number of models is the main factor of difficulty in syllogistic reasoning. In fact, problems generating two or three mental models are more difficult than single-model problems (Johnson-Laird & Bara, 1984).

APPLICATIONS OF RESEARCH TO FACILITATE SCIENCE PROBLEM SOLVING

In order to improve problem solving skills, the standard approach is to look at the processes involved in skilled problem performance and then to derive instructional approaches that will assist practitioners. Researchers have taken four main approaches to deal with the limit of working memory capacity to help students solve problems: *a)* to possess a large knowledge base; *b)* to decrease the information load in problem solving; *c)* to increase students' working memory capacity through specialized training programs; and *d)* to use representations.

Possessing a large knowledge base

In terms of Ausubel's theory (Ausubel, Novak & Hanesian, 1978), if students manage to meaningfully incorporate new knowledge into existing knowledge structure, then we would expect to see relationships between conceptual knowledge after instruction and achievement (Pendley, Bretz & Novak, 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). Humans *chunk* content pieces together, so that very large amounts of content are concurrently accessible. Experts make use of big *chunks* that were developed over those years during which they became experts (Brooks & Shell, 2006).

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 & De Jong (1990) 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.

Decreasing cognitive load

St Clair-Thompson and Gathercole (2006) predict that structuring learning activities in ways that prevent working memory overload, for example by reducing processing difficulty and storage loads as appropriate and by encouraging the use of external memory aids, will enhance learning activities in students with poor working memory function. Alloway (2006) suggests that the learning progress of students with poor working memory skills can be improved dramatically by reducing working memory demands in the classroom. She recommends a number of ways to minimise the memory-related failures in learning activities: by using the instructions that are as brief and simple as possible, by reducing the linguistic complexity of sentences, by breaking down the tasks into separate steps, by providing memory support, by developing effective strategies among students for coping with situations in which they experience working memory failures, etc.

It is useful for the teacher to know that you can change the M-demand (mental demand) of an item (problem) without changing its logical structure. This can facilitate student success by decreasing the amount of information required for processing, that is, avoiding working memory overload (Níaz, 1987a). Johnstone et al. (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 a consequence, to allow greater success for all students but particularly for 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.

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, thus reducing 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).

Improving working memory capacity

Yuan et al. (2006) cite extensive studies on how to improve memory capacity, especially for senior people, but also for secondary students (Yuan, Shavelson, Alonzo, & Steedle, 2007). Although these studies found that extensive practice and memory strategies contributed to the improvement of memory, most of them focused on how to efficiently organize information and establish associations so that the needed information could be retrieved effectively.

According to Turley-Ames and Whitfield (2003), there is little evidence that training working memory in children with low working memory skills leads to substantial gains in academic attainments. However, a study conducted by Klingberg et al. (2005) demonstrated the possibility of improving working memory capacity through computerized cognitive training for children with attention/deficit/hyperactivity disorder. Hence, it seems worthwhile to verify whether computerized cognitive training could increase the working memory of children and adolescents without attention/deficit/hyperactivity disorder (Yuan, et al., 2006, 2007).

Using representations

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 (Vekiri, 2002). 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.

Learners have a limited working memory, and instructional representations should be designed with the goal of reducing unnecessary cognitive load. However, prior knowledge can determine the ease with which learners can perceive and interpret visual representations in working memory (Cook, 2006). Three issues developed from using multiple representations in problem solving: how students use multiple representations when solving problems, how different representational formats affect student performance in problem solving, and how the utilization of representational learning strategies can lead to substantial improvements in problem-solving (Solaz-Portolés & Sanjosé, 2007b).

Physics education literature indicates that using multiple representations is beneficial for student understanding of physics ideas and for problem solving (Larkin, 1985; Van Heuvelen, 1991; Dufresne, Gerace & Leonard, 1997). These representations can include but are not limited to words, diagrams, equations, graphs, and sketches. However, there is less research on thought processes that students use while applying multiple representations in problem solving. The hypothesis of Rosengrant, Van Heuvelen and Etkina (2006) is that students are probably aware intuitively that they do not have the mental capacity to remember all the information in the problem statement, and thus use the representations to visualize an abstract problem situation.

Kohl and Finkelstein (2005) examined student performance on homework problems given in four different representational formats (mathematical, pictorial, graphical, and verbal), with problem statements as close to isomorphic as possible. They found that there were statistically significant performance differences between different representations of nearly isomorphic statements of problems. They also found that allowing students to choose which representational format they will use improves student performance under some circumstances and degrades it in others. In another work, Kohl & Finkelstein (2006a) reported that students who learned physics using lots of representations were less affected by the specific representational format of the problem. Finally, these authors investigated in more detail how student problem-solving performance varies with representation (Kohl & Finkelstein, 2006b). They discovered that student strategy often varies with representation, and that students who show more strategy variation tend to perform more poorly. They also verified that student performance depends sensitively on the particular combination of representation, topic, and student prior knowledge.

Longo, Anderson and Witch (2002) used knowledge representation and metacognitive learning strategies called visual thinking networking. In these strategies students constructed network diagrams which contained words and figural elements connected by lines and other representations of linkages to represent knowledge relationships. Earth science learning was improved in the area of problem solving for students who used visual thinking networking strategies. Chan and Black (2006) investigated what learners need for constructing mental models to understand and reason about systems and scientific phenomena which can be described in text, pictures, and animation. Their results corroborated that, for simple and moderately systems, students did not perform significantly different on learning activities. However, as the systems became more complicated, students who directly manipulated the animation outperformed those in text-only groups and texts-and-static-visual groups on the outcome measures. Mayer's (1999) research pinpointed some conditions under which multimedia learning can lead to substantial improvements in problem-solving transfer. Overall, students make better sense of a scientific explanation when they hold relevant visual and verbal representations in their working memory simultaneously. When multimedia messages are designed in ways that overload visual or verbal working memory, transfer performance is adversely affected.

SUMMARY AND CONCLUSIONS

Working memory concerns that part of the memory system dealing with temporary storage and manipulation of thoughts during cognitive processes. Nevertheless, our information processing systems are often limited by our working memory capacity. Working memory plays a critical role in completing cognitive tasks. Cognitive tasks place extraordinary demands on the management and attentional resources in working memory. Due to the importance of working memory in cognitive activities, performance on cognitive tasks will be affected when information load exceeds individuals' working memory.

A review of available studies on the relationship between working memory and science problem solving revealed that they are positively correlated. The ability to maintain information in a highly activated state via controlled attention may be important for integrating information from successive problem-solving steps. Working memory capacity may also be involved in a number of cognitive variables working as predictors of achievement in science, including: the M-space, the field factor (field-dependence/field-independence) and the mobile/fixed cognitive style. On the other hand, according to the mental model theory, problem solving depends on the construction and manipulation of mental models. Mental models are created in working memory, combining information stored in long-term memory, as well as information extracted from the problem.

Based on the discussion, directions for the improvement of science problem solving skills are suggested. These include the key role of a large knowledge base, to decrease the information load in problem solving, to increase students' working memory capacity through specialized training programs, and to use representations. Using multiple representations when solving problems is beneficial for students; representational formats of problems affect the student's performance, and the utilization of representational learning strategies can lead to substantial improvements in problem solving.

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