Chapter 1

Introduction

1.1 Metacognition in Educational Practice

In their analysis of mainstream education (from elementary to postgraduate levels), Koschmann et al. (1996) argue that it is producing individuals who fail to develop a valid, robust knowledge base; who have difficulty reasoning with and applying knowledge; and who lack the ability to reflect upon their performance and continue the process of learning. Among the failures of the educational system Koschmann et al. (1996) single out the fact that students often do not know when they do not know; and when they are aware of their lack of knowledge, they do not know what to do about it. This ability of knowing what one knows and what one does not know, and thinking about one’s own thinking is often described as metacognitive knowledge or metacognitive skill.

Metacognitive knowledge consists primarily of knowledge or beliefs about what factors or variables act and interact in what ways to affect the course and outcome of cognitive enterprises (Flavell, 1979). The acquisition of this type of knowledge in a learning context produces a distinctive awareness of the processes as well as the results of the learning endeavour. Previous research suggests that metacognition has a number of concrete and important effects on learning. It plays an important role in oral comprehension, reading comprehension, problem-solving, attention, memory, social cognition, and various types of self-control and self-instruction. Metacognitive awareness can lead people to select, evaluate, revise, and abandon cognitive tasks, goals, and strategies (Flavell, 1979).

In general, theories of metacognition focus on (a) the role of awareness and executive management of one’s thinking, (b) individual differences in self-appraisal and management of cognitive development and learning, (c) knowledge and executive abilities that develop through experience, and (d) constructive and strategic thinking (Paris and Winograd, 1990). Theoretical models of metacognition have been proposed and provide a general framework to understand the relationship between the different aspects or components of this phenomenon. One such model, devised by Tobias and Everson (2002) perceives metacognition as a compound of skills and knowledge - knowledge of cognition, monitoring of one’s cognitive and learning processes, and control of those processes. Tobias and Everson have investigated largely the monitoring aspect of metacognition,
based on the assumption that accurate monitoring is crucial in learning and training contexts where students have to master a great deal of new knowledge (Tobias et al., 1999). Thus, their model assumes that the ability to differentiate between what is known (learned) and unknown (unlearned) is a prerequisite for the effective self-regulation of learning. They affirm that this aspect of metacognition supports the development of other metacognitive skills, such as comprehension monitoring, help seeking, planning, and revising.

Recently, many studies have examined ways in which theories of metacognition can be applied to education, focusing on the fundamental question “Can explicit instruction of metacognitive processes facilitate learning?” (Hacker et al., 1998; Hartman, 1998). The literature points to several successful examples (e.g. Derry (1992) and Hacker et al. (1998)), such as Schoenfeld’s studies with maths students (Schoenfeld, 1985, 1987). In his work, Schoenfeld illustrates ways that students can be taught to monitor and evaluate their performance on maths problems. For example, students are required to pause frequently during problem solving and ask themselves questions, such as “what I am doing now?”. Learning is both an active and a reflective process. Though we learn by doing, constructing, building, talking, and writing, we also learn by thinking about events, activities, and experiences (Burns et al., 2000). Self-reflective activities encourage students to analyse their performance, contrast their actions to those of others, abstract the actions they used in similar situations, and compare their actions to those of novices and experts (Goodman et al., 1998). So, when students are engaged in metacognitive activities, such as self-assessment, self-explanation, help-seeking, monitoring, or revising, their learning is enhanced.

Recent research indicates that metacognitively aware learners are more strategic and perform better than unaware learners (Garner and Alexander, 1989; Pressley and Ghatala, 1990; Bransford et al., 1999). One explanation is that metacognitive awareness enables individuals to plan, sequence, and monitor their learning in a way that directly improves performance (Schraw and Dennison, 1994). Research also indicates that weaker students benefit even more than stronger students from such activities (Wong et al., 1997; White and Frederiksen, 1998). However, not all students engage spontaneously in metacognitive thinking unless they are explicitly encouraged to do so through carefully designed instructional activities (Bransford et al., 1999; Chi et al., 1989; Lin and Lehman, 1999). It is therefore important to investigate effective ways of including metacognitive support in the design of natural and computer-based learning environments.

Following Davidson et al. (1994) claim for further research on metacognition in instruction, the area of Computers and Education and more specifically of Artificial Intelligence in Education try to address questions like “How can the use of the metacognitive processes be enhanced, both in and out of natural settings?” Designing metacognitive activities in interactive learning environments (ILEs) that focus on improvements at the domain and metacognitive levels is a theoretical and practical challenge. This integrated approach to metacognitive development involves many aspects of student development: on the one hand including academic competence and on the other, fostering knowledge about the self-as-a-learner.

However, most ILEs and Intelligent Tutoring Systems (ITSs) have regarded metacognition training as a by-product, sometimes addressing metacognition in a tangential way, providing embedded reflection tools, but not overtly targeting metacognitive development or analysing the impacts of such tools on students’ metacognition and attitudes towards learning.
Very few attempts have been made to design explicit metacognitive models into ILEs. One example is MIST, a computer-based system that helps students to actively monitor their learning when studying from texts (Puntambekar, 1995). Its design follows a process-based intervention and uses collaboration, reflection, and questioning as tutorial strategies to facilitate students’ planning and monitoring skills. MIST was rather simple from a computational point of view, but demonstrated success in bringing about some changes to the learning activities of students. Another interesting example is the SE-Coach system (Conati and Vanlehn, 2000); it supports students learning from examples through self-explanations. Conati and Vanlehn (2000) devised a student model that integrates information about the students’ actions with a model of correct self-explanations and the students’ domain knowledge. In this way, the SE-Coach system assesses students’ understanding of examples from reading and self-explanation actions and scaffolds improvements in self-explanation.

Researchers in computer-based ILEs have recognized the importance of incorporating metacognitive models into ILE design (Lin, 2001; Aleven and Koedinger, 2000, for example). However, the lack of an operational model of metacognition makes this task a difficult one. Thus, the development of models or frameworks that aim to develop metacognition, cognitive monitoring, and regulation in ILEs is a fruitful and open topic of investigation.

This thesis is concerned with the creation of a computational model of metacognition instruction within ILEs for problem solving. The model defines which metacognitive skills should be modelled, rules for assessing learners’ metacognitive states, and a range of reflective activities. It proposes a new integrated environment that has an action-reflection-action cycle approach to problem solving and metacognitive development. Reflection on the learning processes, on the learner’s abilities, and on the task is viewed here as an approach to improve metacognitive skills.

Despite their general applicability, metacognitive skills may to some extent be domain specific, and their application and benefits may vary across different types of content areas (Davidson et al., 1994; Davidson and Sternberg, 1998). Therefore, it is important to identify the circumstances in which metacognition can be triggered and applied effectively in a particular domain. In problem solving domains there are many metacognitive processes involved in (1) identifying and understanding the problem, (2) mentally representing the problem, (3) planning how to proceed, and (4) evaluating one’s performance. The successful application of these metacognitive processes depends on characteristics of the problem (whether it is a well-structured or an ill-structured problem), the problem solver, and the context in which the problem is presented.

Theories of problem solving have placed a major focus on the role of heuristics. However, it has been shown that extensive domain specific knowledge and a repertoire of heuristics are not sufficient during problem solving. The student must construct some decision mechanism to select from the available heuristics, or to develop new ones, as problem situations are encountered. Furthermore, Polya (1945) argues that the learner must engage in thinking about the various tactics, patterns, techniques, and strategies available to them. In order to do so, a management function must be incorporated to this activity. This executive function of self-reflection is part of the metacognitive skills needed in problem solving. According to John Dewey, philosopher and educational theorist, to be self-reflective is to explore the various external influences affecting consciousness, such as values, conventions, morality, and belief systems. Significantly, there is,
for Dewey (1933), a period of time in which action must be suspended and during which a person makes his or her judgment of action or behaviour, what some have called reflection-in-action and reflection-on-action (Schön, 1987).

We share Polya’s, Schoenfeld’s, and other researchers’ belief that it is equally necessary to focus on both the cognitive and metacognitive dimensions of problem solving in order to produce good problem solvers. For this reason this thesis investigates how metacognitive skills can be developed in conjunction with problem solving skills. It attempts to ascertain the most relevant metacognitive skills, the best moments in the learning experience to provide metacognitive scaffolding to the student, and the most effective approaches.

1.2 Purpose of the Thesis

This thesis has designed a general computational model of metacognition training for problem-solving learning environments and implemented this model together with a problem-solving ILE. The model, called the Reflection Assistant (RA), uses reflection as a means to improve students’ metacognitive awareness and cognitive monitoring.

The main characteristics of the RA Model are the design of new external representations to reify specific metacognitive skills and the definition of a new automatic metacognitive assessment of knowledge monitoring that is used to build a student metacognitive model.

The RA Model is based on Tobias & Everson’s theoretical model of metacognition, where knowledge monitoring is the primary metacognitive skill to be nourished to achieve a comprehensive metacognitive development. They state that by knowing what one already knows, one becomes aware of the potential knowledge and skills that one can bring to bear, which boosts one’s confidence in one’s own learning. This is an essential attitude for becoming a good maths problem solver. Research in self-regulation also supports this view (Zimmerman, 1998). In our research we follow this assumption and give primary attention to promoting awareness and fostering of knowledge monitoring.

For these reasons we have devised in the RA a mechanism to infer students’ knowledge monitoring levels. In our model two aspects of the learner’s knowledge monitoring skill are modelled: knowledge monitoring accuracy (KMA) and knowledge monitoring bias (KMB). Thus, two scales of measurement for knowledge monitoring are employed:

- The Knowledge Monitoring Accuracy (or KMA) scale provides a profile of the learner’s estimated knowledge of the domain;
- The Knowledge Monitoring Bias (or KMB) scale indicates the bias or inclination in the learner knowledge monitoring ability.

Information about the learner’s prediction of performance compared to her actual performance is used to form beliefs about the current metacognitive conditions and to update the KMA and KMB values.

To achieve its goal, the RA proposes activities that prompt the learner with metacognitive questions, mostly for triggering self-assessment of problem solving and knowledge monitoring. Furthermore, novel graphical reification of metacognitive skills are proposed to provoke self-reflection in order to elicit self-awareness and self-control. The RA Model was used as part of
the design of MIRA, a problem-based interactive learning environment in the domain of algebra word problems.

MIRA is an acronym for “Metacognitive Instruction using a Reflective Approach”. Also, the word *mira* in Spanish is used as an interjection meaning “look!”, “pay attention!”, in the sense of “take time to reflect”. This principle is incorporated in MIRA: it seeks to motivate the learner to observe how she is dealing with the problems and how she is using available resources to complete the learning task.

MIRA was built for the domain of algebra word problems and focuses especially on translating a problem presented in natural language (English) into equations. Thus, at the domain level MIRA provides activities to engage students in developing the skills needed to create linear equations from algebra word problems - it presents a series of algebra word problems and gives students the opportunity to adopt problem-solving strategies such as breaking the problem into individual elements in order to help understanding the task of generating equations. At the metacognitive level, MIRA engages students in reflective activities before and after each problem. The emphasis is on developing students’ metacognitive expertise, particularly their knowledge monitoring skills as well as their ability to reflect on their problem solving processes. The pedagogical strategies include asking students to judge their comprehension and ability to solve the problems proposed, supplying activities to scaffold their reflections, and introducing them to methods for monitoring and reflecting on the learning process. The information generated by the interaction with the problem solving resources available in MIRA and the time spent in activities are used to inform the metacognitive feedback.

The main hypothesis driving the research is that reflection on the metacognitive skills between problem-solving learning activities could enhance:

1. Students’ awareness of their own abilities to solve that type of problem;
2. The selection and use of metacognitive and cognitive strategies;
3. Students’ monitoring process;
4. Students’ performance on the topic in hand.

It was expected that the MIRA system would help students to become more aware of which metacognitive skills they use when they are solving problems and how they use them. By reflecting on these issues it was expected that those students would:

1. Increase their understanding of their own learning processes;
2. Improve their use of metacognitive knowledge and skills;
3. Generate a better understanding of the influence of these skills on the outcomes of the tasks performed.

In summary the goals of this research were:

- To develop a model of metacognitive instruction for interactive learning environments based on problem solving - the Reflection Assistant Model.
- To design and implement an interactive learning environment that incorporated the RA model - the MIRA system.
• To evaluate the effectiveness of the RA and MIRA in fostering metacognitive skills and maths problem-solving performance in students. For this purpose, two versions of MIRA were developed (with and without the reflective activities) and a comparative laboratory evaluation was undertaken.

1.3 Research Methodology

This research used education theories, theoretical constructs in metacognition and research on problem solving, together with empirical observations of real students to inform the design of the RA Model and the MIRA system. We have validated their design with prototypes, which were evaluated by real users. This approach conforms the second and third methodologies for modelling teaching tactics and strategies for tutoring systems as proposed by du Boulay and Luckin (2001). Both methodologies start from a learning theory and derive appropriate teaching tactics and strategies from that theory. The third methodology is also based on observation of students.

Quantitative and qualitative analysis of the evaluation done guided the interpretations of the results and contributions of this research. The “quantitative” aspect stemmed from measuring metacognitive and learning performance variables and analysing the relationships among them with descriptive and inferential statistics. The “qualitative” analysis was based on students’ evaluation of their interaction with MIRA and observations of the students.

Preliminary observations of students in the classroom also supported parts of this research, when it was noted the different ways in which students perceive, experience, and understand their metacognitive skills.

The research was conducted in a phased approach. The phases and main activities are summarised below:

Phase I: Preliminary Studies. The research started in October, 1998. The first year was spent reading the relevant literature in the fields of educational psychology, Interactive Learning Environments (ILEs), and Artificial Intelligence in Education (AIED), and organizing the thesis proposal.

Phase II: Experimentations and Model Building. The second and third years were dedicated to a more in-depth understanding of metacognitive development and problem solving processes, and how students perceived their metacognitive skills in classroom settings. The issue of how metacognition can be taught in an ILE was central to the definition of the Reflection Assistant Model, leading to investigations of appropriate pedagogical approaches to be adopted in the model. As a consequence, some pilots empirical studies were conducted, ranging from questionnaires and observations of classroom activities to the development of a prototype that incorporated a draft version of the Reflection Assistant Model.

Phase III: Implementation and Empirical Study. The first task was to select a domain for the learning topic in the learning environment. The selection of a suitable domain for testing out the model was not straightforward. A shortage of subjects for the main experiment and difficulty accessing literature on problem solving for the domain impacted in the final choice. Initially we tried a topic in the domain of Computer Science (problems about finite states machines). Eventually we chose algebra word problems, as they require less specialized previous knowledge, making it easier to find subjects for the experiment.

The first part of the final period of the research was dedicated to refining the Reflection Assistant Model and to reading the relevant literature in Algebra Problem Solving. Then the
design and implementation of the MIRA learning environment were carried out. The main experiment was conducted and the results were analysed.

1.4 Structure of the Thesis

Chapter 1 introduces the research topic and presents an overview of the research questions, the main hypothesis put forward, and the methodology of the research. It also presents the general organization of the dissertation.

Chapter 2 contains a survey of theories of metacognition, focussing on the role of metacognition in learning through problem solving. It introduces representative theoretical models of metacognition, among which is the componential model of metacognition proposed by Tobias & Everson that is used in this thesis. The issue of measuring metacognitive states and changes is discussed and some methods and instruments are presented. Operational definitions of reflection and self-reflection are discussed. Finally, empirical studies on instruction of metacognition, assessment instruments for metacognition and reflection are used to frame the research questions.

Chapter 3 examines reflective tools and other attempts to design metacognitive activities in Interactive Learning Environments (ILEs) and Intelligent Tutoring Systems (ITSs). A basic design classification is proposed and examples from the literature are organized into this classification.

Chapter 4 discusses the proposed computational framework, which incorporates metacognitive instruction through reflective activities - the Reflection Assistant (RA) Model. It offers a rationale for the RA Model and sets its theoretical bases. The RA Model adapts Tobias & Everson’s hierarchical model of metacognition, and incorporates their knowledge monitoring measurement instrument in the form of rules for an automatic inference engine. The engine produces metacognitive scores and proposes reflective scaffolding according to these scores. The RA architecture and components are presented. It concludes with a more detailed discussion of the research questions and the hypothesis put forward in this thesis.

Prior to the introduction of the MIRA learning environment, Chapter 5 presents the domain of algebra word problems. It focuses on the processes and skills involved in translating a word problem into an equation. Definitions of terms employed in MIRA are presented, along with examples of algebra word problems and some ILEs and ITSs used in this domain. In the MIRA system a specific tool was conceived to help students at the domain level - the PAL Tool. The goals, design features and functionality of this tool are presented.

Chapter 6 and Chapter 7 are dedicated to the MIRA interactive learning environment. Chapter 6 gives an overview of MIRA from the user’s perspective, showing the typical flow of student activities within the system. Chapter 7 describes the design of MIRA. The implementation of the Reflection Assistant model in MIRA is explained together with the adaptations needed to fit the maths topic taught in MIRA.

Chapter 8 presents the experimental study of this research. It was an empirical evaluation of students’ interaction with MIRA focusing mainly on the observation of metacognitive and performance changes. The experiment was undertaken with undergraduate students at the University of Sussex. The design of the experiment is presented, together with the materials and data collected. It also presents the statistical analysis. The observations and analysis are used to formulate more general answers for the research questions proposed. The limitations of the experiment are also
Chapter 1. Introduction

Chapter 9 summarises the results and main contributions of this thesis. It considers the validity of the RA Model for promoting the development of metacognitive awareness and growth of reflective behaviour. It re-examines the relationship between metacognitive changes and performance gains. The chapter critiques the approach taken in the thesis and outlines further lines of research.

Parts of the work described here have been presented at the following International Conferences: ED-MEDIA (Gama, 2000b), ITS (Gama, 2000c), AIED (Gama, 2001c), and International Conference on New Technologies in Science Education (Gama, 2001a); and in the Brazilian Symposium of Informatics in Education (Gama, 2003).

Working papers with preliminary results of this research were also presented at the annual Human Centred Technology Postgraduate Workshop at the University of Sussex (Gama, 1999), (Gama, 2000a), (Gama, 2001b), and (Gama, 2002).