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Design and Validation of a Multimethod Assessment of Metacognition and Study of the Effectiveness of Metacognitive Interventions

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DESIGN AND VALIDATION OF A MULTIMETHOD ASSESSMENT
OF METACOGNITION AND STUDY OF THE EFFECTIVENESS
OF METACOGNITIVE INTERVENTIONS

A Dissertation
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy
Chemistry

by
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August 2008

Accepted by:
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ABSTRACT

The central role of metacognition in learning and problem solving, in general and in chemistry in specific, has been substantially demonstrated and has raised pronounced interest in its study. However, the intrinsic difficulties associated with the inner processes of such a non-overt behavior have delayed the development of appropriate assessment instruments. The first research question addressed in this work originates from this observation: Is it possible to reliably assess metacognition use in chemistry problem solving? This study presents the development, validation, and application of a multimethod instrument for the assessment of metacognition use in chemistry problem solving. This multimethod is composed of two independent methods used at different times in relation to the task performance: (1) the prospective Metacognitive Activities Inventory, MCA-I; and (2) the concurrent Interactive MultiMedia Exercises software package, IMMEX. This work also includes the design, development, and validation of the MCA-I; evidence is discussed that supports its robustness, reliability and validity. Even though IMMEX is well-developed, its utilization as a metacognition assessment tool is novel and explained within this work. Among the benefits of utilizing IMMEX are: the automation of concurrent evidence collection and analysis which allows for the participation of large cohorts, the elimination of subjective assessments, and the collection of data in the absence of observers which presumably favors a more realistic deployment of skills by the participants. The independent instruments produced convergent results and the multimethod designed was proven to be reliable, robust and valid for the intended purpose. The second guiding question refers to the development of
metacognition: Can regulatory metacognition use be enhanced by learning environments?

Two interventions were utilized to explore this inquiry: a Collaborative Metacognitive Intervention and a Cooperative Problem-Based Laboratory Project. The former was designed and developed as part of this study; the latter is part of the curriculum of a two-semester cooperative General Chemistry Laboratory course. Both interventions rely on two main axes to promote metacognition development: intense social interaction and induced reflection. In the first case, it is through small group collaborative work and guided and peer prompting; in the second one through cooperation and inquiry in the laboratory. The effect of both interventions was investigated using pre and posttest, control and treatment type experiments. The choice of assessment was the multimethod developed in the first part of this same study. Despite the differences between the interventions (length, nature of prompting, and relation to chemistry contents) both learning environments succeeded in enhancing the awareness and use of metacognition in chemistry problem solving. Findings support the assertion that the mechanisms that define the learning environments under study—social interaction and reflection—promote the enhancement of metacognitive skills. A significant corollary of this research is that it offers evidence of the laboratory as a learning environment where students can acquire high order thinking skills and develop content knowledge and understanding.
DEDICATION

This dissertation is dedicated to Dr. Lyle C. Hall, Professor Emeritus, University of Wisconsin-River Falls, whom I admire and whose example I hope to follow.
ACKNOWLEDGMENTS

I would like to acknowledge my research adviser, Dr. Melanie M. Cooper, who procured at all times to create the conditions necessary for success. Dr Cooper set high standards and provided the guidance and support to expect corresponding performance. I would also like to thank Dr. Gautam Bhattacharyya who has always made himself available for academic discussion and has been a great help and a source of insightful ideas; Dr. Jeff Marshall and Dr. Larry Grimes for being part of my doctoral committee and for their input. I would like to thank Todd Gatlin for frequent discussions about our topics of research interest and for contributing fruitful ideas and different informed perspectives, especially of ontological and epistemological nature. I would also like to acknowledge Dr. Ron Stevens and the staff at the IMMEX Project for their support processing IMMEX data, Beth Walls, and present and former members of Dr. Cooper’s research group. The work presented here would not have been possible without the collaboration of Mrs. Barbara Lewis and the teaching assistants, and the participation of general chemistry students.
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CHAPTER ONE
INTRODUCTION

Most chemistry college level teachers come to teaching without any formal pedagogical training. There is a tacit assumption that content knowledge qualifies individuals to teach in their area of expertise. Custom and tradition prevail as there is a tendency to reproduce and perpetuate the type of instruction one was exposed to as a student. There are intrinsic difficulties associated with learning science concepts, which are only augmented by the often complex threefold levels of representing and understanding chemical concepts: macroscopic, microscopic and symbolic (Johnstone, 1991). For most individuals the exercise of bringing these three representational levels into a coherent understanding is not a trivial task. However, the main barrier for understanding chemistry may not be its intrinsic complexity but more so the methods employed to facilitate its learning (Gabel, 1999). The fundamental goal of chemistry education research and scholarship should be to inform chemistry teaching and learning practices thereby improving the outcome of these complementary activities (Herron & Nurrenbern, 1999). Unfortunately, research has not always had much influence on the way chemistry is taught and learned (Gabel, 1999; Phelps & Lee, 2003), at least not as much as intuition and opinions (J. N. Spencer, 2006; J. N. Spencer, 1999) (Johnstone, 1997). Spencer (J. N. Spencer, 1999) maintains that “emphasis has been on providing instruction rather than producing learning”, to the point where students can produce correct (or at least acceptable) answers without true understanding of the chemical concepts and implications.
Many as Thomas (G. P. Thomas, 2006) have reflected “what other long-life attributes, apart from learning and understanding science, might and should be developed in students within their science learning environments?” Effective chemistry science instruction should not only increase chemical learning and understanding but also promote students’ learning autonomy and prepare them to be life long learners (Schraw, Crippen, & Hartley, 2006). This consideration gains relevance when one thinks that most students will not even move on to higher level chemistry courses. Teaching for metacognition enhancement has been identified in science education literature as a way to achieve this broad objective (Gunstone, (Schraw et al., 2006) and in fact it has been suggested that it is strategic use more than knowledge in itself that ultimately improves learning (Schraw, Brooks, & Crippen, 2005).

Metacognition can be initially thought of as the strategies and skills necessary to understand a task that is being performed. This implies the ability to use the task or goal appropriately and discuss its use (Brown, 1987)(p. 65). Metacognition occurs when individuals monitor and evaluate their own cognitive behaviors in a learning environment (Ayersman, 1995) or problem space. The influence and relevance of metacognition in learning and problem-solving has been substantially demonstrated, and in fact it has been shown to compensate for lower cognitive abilities (Swanson, 1990).

It is not surprising then that over the last three decades, a great deal of interest in instructional enhancement of metacognition use has surged (Blank & Hewson, 2000; Davidowitz & Rollnick, 2003; Desoete, Roeyers, & De Clercq, 2003; Georgiades,
including the use of specific strategies in chemistry (Francisco & Nicoll, 1998; D. Rickey & Stacy, 2000; Schraw et al., 2005; Tsai, 2001).

The assessment of metacognition is made intrinsically difficult because it is not an overt behavior; it is not only an array of inner processes but rather often individuals are not fully aware of them. The vast majority of the studies carried out on the measurement of metacognition have relied on procedures like systematic observation or think aloud protocols which are extremely time consuming and inadequate for the rapid identification of metacognitive levels. Correspondingly, a current need for reliable metacognition measurement instruments has been reported. Ideally, these instruments would also offer the possibility to evaluate the effectiveness of metacognitive learning environments.

This work addresses these two prime questions in the field of metacognition research: the assessment of the construct itself and the effectiveness of interventions designed to promote its development and use.

**Research Goals**

Two fundamental questions guided the development of this research project:

1. Can regulatory metacognition use in chemistry be reliably assessed by means of a multimethod design composed of a prospective self-report instrument followed by a concurrent assessment?
2. Can regulatory metacognition use in chemistry be modified by instructional interventions such as a collaborative paper and pencil activity and a cooperative problem-based laboratory project?
It is the interest of this work to contribute to the advancement of these two pivotal areas of research in metacognition. By focusing specifically on the field of chemistry, the findings of this project will be able to inform its teaching and learning thereby addressing the fundamental goal of chemistry education research. To accomplish this objective, a set of six research goals was derived from the guiding questions:

1. Design, validation and implementation of a prospective self-report instrument (Metacognitive Activities Inventory, MCA-I) to assess student use of regulatory metacognition in chemistry problem-solving. This inventory is foreseen as the first component of the multimethod instrument. Its intended qualities are: validity, high reliability, short administration time, and simplicity in its use, interpretation and administration.

2. Implementation of IMMEX (Interactive Multi-Media Exercises) as a concurrent assessment of metacognitive skillfulness. Given that this web-based problem space requires of metacognition use to work through the assignments, it is hypothesized that different levels of metacognition use would be reflected on the quality of the strategies employed by students and that these strategies could be characterized in terms of metacognition use. Traditionally, concurrent methods utilize very time consuming protocols like think aloud, systematic observation, and qualitative protocol analysis of responses generated by participants. IMMEX introduces a novel way of accomplishing metacognition activity assessment. Amongst its characteristics it has the capability of automatically creating records of students’ actions. As it will be detailed later (Chapter IV) protocol analysis is
automated through the modeling of a large number of performances which enables the creation of a reduced number of metacognition descriptors with which students can be rapidly classified.

3. Convergence study of the prospective (MCA-I) and concurrent (IMMEX) assessment instruments. The principle of across method and across time assessment is to collect information that comes from using two different instruments utilized at different times in relation to a task. The MCA-I is a prospective—before the task—self-report assessment. Complementarily, IMMEX is concurrent and generates data based on the actual deployment of metacognitive activities and not on reports coming from the participants. The fundamental idea is gathering independent data that do not share sources of error. Contrasting the information collected with the two instruments allows determining the level of validity of the measurements as a whole.

4. Design of a collaborative paper and pencil intervention to promote metacognitive awareness and use. A collaborative protocol that creates a reflective environment is envisioned as a way to promote general metacognitive skillfulness. It is based on initially developing a cognitive imbalance and then using prompts to guide students to think critically about their problem-solving strategies and skills. Participants negotiate meanings, decisions, solutions and conclusions working in a small group (two or three students).

5. Study of the collaborative metacognitive intervention effectiveness in developing metacognition use and awareness, and problem-solving skills and
performance. An experimental control/treatment, pre and posttest design was chosen to study the effect of completing this task. Assessment is to be conducted by using the multimethod.

6. Study of the effect of a cooperative problem-based laboratory project on metacognition use and awareness, and problem-solving skills and performance. There is vast literature suggesting that cooperative problem-based laboratory promotes the use of metacognition through social interaction and inquiry based learning. The multimethod instrument is proposed to verify this premise by comparing students after having the laboratory experience with others without such experience.

Chapter II reviews relevant literature in the field of metacognition, its assessment and its instruction. Chapters III through VI describe and discuss the work done and results obtained in the process of completing the six research objectives aforementioned. Chapter VII returns the focus to the research guiding questions; answers to these questions are presented here, as well as a discussion of the impact of the findings originated from this work and of their implications in education. Chapter VII also addresses related and future studies.
CHAPTER TWO

LITERATURE REVIEW

Introduction

The goal of this section is to expand on the brief introduction to metacognition provided in Chapter I. This chapter provides an overview of the research that has been done regarding its assessment and development through instruction, a further topic covers aspects related to metacognition study in the context of chemical education research.

Metacognition

Despite the numerous definitions encountered in literature (Kauffman, Ge, Xie, & Chen, 2008), probably the most common description for metacognition is “knowledge and regulation of one’s own cognitive system” (Brown, 1987). The term metacognition was originally coined by Flavell in the early 70’s who described it as “knowledge and cognition about cognitive phenomena” (Flavell, 1979). However, Brown (Brown, 1987) maintains that the concept itself and the kind of activities we now call metacognitive were recognized and studied by educational psychologists like Dewey, Huey and Thorndike as early as the first part of the twentieth century. As example, Brown cites Dewey’s system of inducing reflective reading which supported “active monitoring”, “critical evaluation”, and “seeking after meaning and relationships” (Brown, 1987) (p. 67), all of which are metacognitive in today’s jargon. According to Tsai (Tsai, 2001) it was Vygotsky who introduced the idea to modern times when he asserted that “consciousness and deliberate control are the principal contributions of the school years”. Charles Edward Spearman, as cited by Georghiades (Georghiades, 2004a), stated that:
“Such a cognizing of cognition itself was already announced by Plato. Aristotle likewise posited a separate power whereby, over and above actually seeing and hearing, the psyche becomes aware of doing so” thereby positioning the origins of pondering about metacognition way before our time.

Metacognition may be more easily understood as “awareness of how one learns; awareness of when one does and does not understand; knowledge of how to use available information to achieve a goal; ability to judge the cognitive demands of a particular task; knowledge of what strategies to use for what purposes; and assessment of one’s progress both during and after performance” (Gourgey, 2001). Metacognition differs from cognition in its being necessary to understand how a task is performed whereas cognition is necessary to simply perform the task (Schraw, 2001). The influence and relevance of metacognition in learning and problem-solving has been extensively demonstrated (Georghiades, 2000; Kauffman et al., 2008; Pintrich, 2002; Schraw et al., 2005; Veenman, Elshout, & Meijer, 1997). For example, Swanson (Swanson, 1990) used a questionnaire-interview format with multiple raters to investigate how different levels of metacognitive knowledge influenced problem-solving performance in grades 4 and 5 children. Participants who scored in the gifted range on standardized cognitive ability and achievement-tests were classified as high-aptitude; those scoring in the low to average range were classified as low-aptitude. Children’s problem-solving performance was analyzed using think-aloud protocols as they provided solutions to assigned tasks. Swanson’s findings suggest that, regardless of aptitude, children with higher metacognitive levels outperformed those with lower metacognitive activity. These results
suggest that metacognition and general aptitude are independent constructs, and that a higher level of metacognition may compensate for lower aptitudes. Others have also suggested that it may play a compensatory role for cognitive skills and motivation in the learning of chemistry (Schraw et al., 2005). Ayersman (Ayersman, 1995) argues that not being aware of how their cognition operates, impedes students to understand why they continue failing on a given task and why their trying harder does not lead to more successful solutions. Metacognition has also been found to be a useful predictor of efficient learning (Veenman, Kok, & Blote, 2005) and problem-solving (Howard, McGee, Shia, & Hong, 2000; Rozencwajg, 2003). Veenman (Veenman et al., 2005) assessed metacognitive skillfulness of secondary school students through systematic observation and determined that it has a positive effect on learning and performance of a mathematical task. Similarly, Rozencwajg (Rozencwajg, 2003) used interviews and the ability of seventh graders to allocate resources in relation to a task’s difficulty to show that there is a direct relation between metacognitive level and problem-solving skills.

According to Thomas and McRobbie (G. P. Thomas & McRobbie, 2001), the enhancement of metacognition use resulting in improved learning outcomes should not be surprising since students are most efficient in their learning when the learning environment promotes understanding, accessing learning repertoires and reflection. In accordance with this argument, Gilbert (Gilbert, 2005) has described the use of metacognition in the processes of visualization, which he refers to as “metavisualization”, as necessary, and asserts the prevalent role of metavisual skills in the learning of science.
There are two main metacognition components generally identified: metacognitive knowledge or knowledge of cognition, and metacognitive skillfulness or regulation of cognition (Davidson, Deuser, & Sternberg, 1995; Schraw & Moshman, 1995). Knowledge of cognition refers to the awareness of the individuals about their cognition, that is: knowing about things (declarative knowledge), knowing how to do things (procedural knowledge) and knowing why and when to do things (conditional knowledge). Research indicates that this component is late developed and in general explicit though in some instances this explicit awareness is not necessary for knowledge of cognition to be useful (Schraw et al., 2006).

Regulation of cognition is the executive component that comprises the repertoire of activities used by individuals to control their cognition. Researchers have identified a number of different regulatory activities grouped under three subcategories: planning, monitoring and evaluating. These regulatory skills guide problem-solving, and their refinement is believed to bring improved efficiency in solving problems and other tasks (Davidson et al., 1995). Planning refers to selection of strategies and allocation of resources; monitoring describes the ability to track one’s comprehension and/or accuracy of performance as the task is carried out; evaluating refers to the ability to critically assess the outcomes and processes of one’s learning or problem-solving. These regulatory processes are not explicit in many situations, one reason being that they become highly automated in adults, especially experts in a domain (Butler & Winne, 1995; Schraw et al., 2006). Unambiguous classification of activities into one of these three subcomponents is not always warranted; there have been reports of considerable overlapping, for example,
that a process considered as monitoring under given circumstances may be seen as evaluative under others (Schraw & Dennison, 1994). The theoretical framework aforementioned is used as the foundation for the work described here; however, the interest is specific to metacognitive skillfulness since it directly affects “what you do when you don’t know what to do”, (Wheatley, 1984) the working definition for problem-solving used in this context.

**Metacognition in College Chemistry Learning**

It has been claimed that metacognition characteristics make its role in chemistry learning fundamental to achieve deeper and fruitful understanding (D. Rickey & Stacy, 2000). Despite the consensus about its relevance (Francisco & Nicoll, 1998; D. Rickey & Stacy, 2000; Schraw et al., 2005), little work has been done to study metacognition in the specific context of chemistry learning. Tsai (Tsai, 2001) suggested the potential of using internet-based environments to facilitate practicing metacognitive skills in chemistry courses, as example this author cited monitoring and reviewing of navigating and learning paths, and sorting out and classifying of information. In a study of the multiple teaching methods in a General Chemistry course, Francisco and Trautmann (Francisco & Nicoll, 1998) utilized three interactive approaches (cooperative learning, concept maps, and class discussion) in addition to traditional lecture. Using a survey, they found that students reported higher levels of engagement with the non-traditional teaching styles. Similarly, they found that students assigned different functions to the different formats employed. From these self-reports on level of engagement and functions served, the authors concluded that “multiple modes of learning foster meta-cognitive (sic) skills
necessary for mastering General Chemistry”. However, the nature of this study is very speculative as it does not present data corresponding to the actual effect on metacognition use or course achievement. Often, it is assumed that metacognition occurs if that is the intention of the instructor or if an argument for the observed positive outcomes is necessary. In some instances, this amounts to conveniently equating the intended and implemented curricula with the learned curriculum rather than actually assessing metacognition.

Schraw and collaborators (Schraw et al., 2005) introduced the “Interactive Compensatory Model of Learning” (ICML) as a tool to improve chemistry teaching. This speculative model is based on empirical data and has five components: cognitive abilities, organized knowledge, learning strategies, metacognition abilities, and motivational beliefs. The purpose of their paper is to facilitate teachers’ understanding of how to develop more efficient learning environments and includes suggestions as how to improve the previously mentioned components. These suggestions are general in nature and could be implemented in different science education contexts. Another relevant aspect of the scarce literature in the field is that references to the use or the importance of metacognition in chemistry are not domain specific (Schraw et al., 2006). An exception in this regard is the instantiation of the MORE Thinking Frame in the chemistry laboratory (D. Rickey & Stacy, 2000). MORE (Model-Observe-Reflect-Explain) is believed to promote chemistry specific metacognitive skills, for example, establishing the connections between macroscopic and molecular level explanations (D. Rickey & Stacy, 2000), and in general is it assumed that it explicitly encourages reflection and
metacognition (Tien, Teichert, & Rickey, 2007). In an experimental study (D. Rickey, 1999), participants in a chemistry laboratory course designed around the MORE thinking frame showed “significantly enhanced metacognitive abilities, understanding of fundamental chemistry ideas, and abilities to solve examination problems”. The source of evidence supporting the effect on metacognition was essentially qualitative in nature: including analysis of video and audio recordings of student working in the laboratory and on transfer problems, and interviews that explored students’ perception of laboratory activities.

Metacognitive development in a chemistry related course has been described by Case and collaborators (J. Case, Gunstone, & Lewis, 2001). In their work, the authors modified a second year chemical engineering course (Materials and Energy Balances) to explicitly develop metacognition by “posing questions to the students”, “getting them to try problems on their own”, “discuss issues with their classmates”, “report back to the class”, and “ask questions”. In addition to these activities, students were required to keep a journal with weekly tasks aimed at encouraging their reflection about learning, progress and the course format. Sources of data were the journal entries of 90 students and five individual interviews. Case’s findings suggest that metacognition development occurred; however, the study does not provide information about the effect on achievement or understanding of material. Another aspect that should be considered is the fact that in the course program, during instruction, and through the assignments, the instructor’s expectations to develop metacognition were explicitly shared. This may be a source of
bias for the students who are explicitly assessed on the fulfillment of the expectations of the instructor. In addition, researcher-bias questions may arise from this study design.

Utilizing a case study approach, Davidowitz and Rollnick (Davidowitz & Rollnick, 2003) investigated the effectiveness of using a metaphor, “The Competency Tripod”, and flow diagrams in enhancing chemistry students’ metacognition use. Students were presented with an analogy: The legs of a laboratory tripod are thought of as declarative knowledge, communicative competency, and procedural knowledge; the ring holding the legs together is the link that can be made between the three components or the coherence unifying concept; and the wire gauze represents other factors like the human interaction and time management. The Competency Tripod was assumed to enable metacognition by making students reflect about their learning process in a university second year chemistry laboratory. Implementation took place as part of their post laboratory questions when students were prompted to use the model to reflect about the lab experience. As part of the pre laboratory, students were required to summarize the experiment in a flow diagram that had to be approved by the instructor before the student was allowed to proceed on to laboratory work. The authors collected multiple data from several sources but their analysis revolved around interviews with a stratified sample consisting of four students. Due to the nature of the theoretical framework chosen for the study, the analysis is entirely interpretative and the authors’ interpretation was that metacognition enhancement had occurred. However, this conclusion seems more a consequence of the ubiquitous belief that metacognition development simply happens if it is the instructor’s objective. In the authors’ own words: “It is not possible to establish
directly if the Competency Tripod model was responsible for enabling metacognition in students but like dropping a pebble into a pond, its introduction certainly provided ripples which could be identified as metacognition” (Davidowitz & Rollnick, 2003). Davidowitz and Rollnick’s study exemplifies a common hindrance in the study of the effectiveness of intervention in developing metacognition: the lack of adequate assessment instruments and protocols. The current state of the assessment is discussed in the following section.

**Assessment of Metacognition**

Despite the efforts to raise awareness about and promote instruction in and use of metacognition, work in developing its assessment has not paralleled the interest. The challenge of this enterprise has been well recognized and documented (Everson & Tobias, 1998; Larkin, 2006; D. Rickey & Stacy, 2000) and is believed to be linked to its being an “inner awareness or process, not an overt behaviour” (G. P. Thomas & McRobbie, 2001) which creates intrinsic difficulties in characterizing patterns of thought and strategy development. The lack of appropriate assessment continues to be an obstacle for the advancement of research. There is still a current need for instruments to measure metacognition and related constructs in an easy, time-efficient and reliable manner (Sperling, Howard, Miller, & Murphy, 2002; Veenman et al., 2005).

The assessment of metacognition was recently reviewed by Veenman (Veenman, 2005) who describes the methods in terms of their temporal relation to the performance of a task: prospective, if administered before the task; concurrent, during the task; and retrospective, after the task. Measurement can also be defined by the type of instruments
employed: self-report (i.e. inventories and interviews) or objective behavioral measures (i.e. systematic observation, think aloud protocols).

Concurrent assessment of metacognition in science has been traditionally practiced by using instruments that are very time consuming and require individual evaluation of participants (D. Rickey, 1999; Veenman, 2005). Predominant methods, such as think aloud protocols, and systematic observations, furnish a dense multi-variable description of the participants and are very informative for the researcher but not as useful for the practitioner. Others, like analysis of note taking are not as informative and rely on a lesser number of descriptors. On the other hand, in the array of prospective and retrospective procedures, questionnaires and scales allow a rapid assessment of a large number of participants. However, even if they refer to problem-solving, these instruments rely on the recollection of the habitual performance or of a recent task and not on the actual deployment of the skills. In addition to reliance on the student’s capability of reconstructing and recalling experiences, other issues that present a challenge for self-report are the selection of a reference point and social desirability. In these cases, participants’ responses may be affected by their own expectations and the perceived expectations of others (Thorndike, 2005).

In his review, Veenman (Veenman, 2005) stresses the potential of methodologies that use more than one instrument, that is, *multimethod designs*, especially those which use different types of instruments administered at different times in relation to the performance of the task, namely *across-method-and-time* design. The convenience of measuring metacognition using multiple methods that do not share the same source of
error is supported by other researchers (Garner, 1988; Georghiades, 2004a). Veenman (Veenman, 2005) also suggests that concurrent instruments are more useful for the assessment of metacognition than those that are prospective or retrospective since the former occur as the skills are being deployed while the latter are second order approaches, meaning it is not the skill what is observed but the report about the skill. Multimethod assessment design presents itself as an effective solution to tackle the shortcomings of using instruments separately. A handful of reported studies, focused especially on text reading and studying, do use multiple methods but most show little or no concordance between them (Pintrich, 2002; Veenman, 2005). No attempts using multiple methods have been made to investigate problem-solving at the tertiary level.

Additionally, assessment of metacognitive activities has seldom been attempted in college science courses. A review of the literature did not produce evidence of an instrument specific in identifying metacognitive skillfulness of college science problem solvers. Participants in studies of metacognition have been drawn more commonly from other scholastic levels and areas of knowledge. For example: self-report instruments for use at college level cover areas like reading strategies for comprehension, studying (Taraban, Kerr, & Rynearson, 2004), and learning in social sciences (Everson & Tobias, 1998; Schraw & Dennison, 1994).

Several researchers have noted that college instructors interested in developing learning and problem-solving skills through facilitating of metacognition use would benefit from having an adequate assessment instrument to determine changes in the use
of metacognitive activities (Everson & Tobias, 1998; D. Rickey & Stacy, 2000). Typical assessments reported in literature are described in the following paragraphs.

Schraw and Dennison (Schraw & Dennison, 1994) reported the construction of a 52-item self-report instrument to assess adult’s metacognitive awareness in learning tasks, the Metacognitive Awareness Inventory or MAI, and its administration to 197 undergraduates enrolled in an introductory educational psychology course. Among their goals was generating an inventory suitable for adults that would readily identify metacognitive learners. Their restricted factor analysis findings strongly supported the two-component model of metacognition: knowledge and regulation of cognition. On the other hand, during unrestricted factor analysis, items did not unambiguously fall in a single factor or did shift from one factor to another in different administrations. This behavior is referred to as shift effects and hinders more detailed structural information. Significant relationships between these two components and between the measures of MAI and student performance were found. The MAI was modified by Sperling and collaborators (Sperling et al., 2002) to make it suitable for the assessment of metacognition in children in grades 3-9. Their findings showed that the correlation of the modified instrument, Jr. MAI, with a reported survey on seventh graders metacognition use in math word problem (Fortunato, Hecht, Tittle, & Alvarez, 1991) was high, and that its correlation with overall achievement score was significant, yet low. Exploratory factor analysis of the Jr. MAI was consistent with that for the parent instrument: Clustering beyond the two main factors, knowledge and regulation of cognition, was not possible due to high item shifting.
Everson and Tobias (Everson & Tobias, 1998) used a calibration approach to investigate the relationship between the ability to estimate knowledge and the performance on a related task. This kind of approach has been employed by other authors (Vadhan & Stander, 1994) and it usually looks at a single aspect of metacognition. In this case, the authors focused on knowledge monitoring accuracy or KMA: Participants were asked to predict their vocabulary knowledge using a word list that was later used on a performance test. Association of KMA scores with achievement in English was significant, whereas no significance was detected in its association with performance in science courses. Even though evidence supports the predictive value of this kind of instrument in very specific areas, its strength as assessment of multiple factors of metacognition is limited. This kind of assessment is rendered of little research impact by the limitations of scope and the lack of evidence supporting its predictive ability in the performance of unrelated complex tasks that elicit and demand higher use of metacognition.

Review of common chemical education research literature revealed the absence of investigations addressing the systematic quantitative assessment of metacognition in chemistry context. Again, this is not surprising as consequence of the intrinsic difficulties associated with the assessment of inner, not-overt behavioral constructs. It also unveils a challenging exploration ground for chemistry education researchers and constitutes a foundation of the work conducted in this dissertation.
Metacognitive Instruction

Hartman (Hartman, 2001) maintains that teaching metacognitively entails two complementary processes: teaching with and teaching for metacognition. While teaching with metacognition instructors are engaged in applying their metacognitive skills on the task at hand: teaching. Teaching for metacognition is more relevant for the purpose of this study and is defined as the creating of learning environments that are conducive to activating and developing students’ metacognition awareness and use. It may occur in the form of isolated short duration pedagogical protocols; this is the nature of most studies on metacognition that use interventions for an allocated time (Georghiades, 2006). A different approach consists of blending metacognition in the context of instruction, making of metacognitive skillfulness an intrinsic common factor that threads learning activities. For instance, Georghiades (Georghiades, 2006); used this approach in studying the role of metacognitive activities in elementary students’ use of the conception of science; Thomas and McRobbie (G. P. Thomas & McRobbie, 2001) employed it in their study of using a metaphor for learning to improve metacognition, and Case and collaborators (J. Case et al., 2001) used it in the investigation of metacognitive development in a chemical engineering course.

Similarly, Schraw and collaborators (Schraw et al., 2006) presented metacognition as a part of a broader perspective on learning in the context of self-regulation. The authors summarized six general instructional techniques that can be used across science education to promote the development of metacognitive strategies as well as cognitive skills and motivational aspects. Entire instruction paradigms have been
developed that can be understood as teaching for metacognition environments. An example cited previously is the MORE Thinking Frame utilized by Rickey (D. Rickey, 1999; D. Rickey & Stacy, 2000) in the General Chemistry Laboratory. This strategy explicitly intends to engage students in metacognitive functions throughout their experimental inquiry.

Cooperative problem-based laboratory instruction is another learning environment that promotes the use and development of metacognitive skillfulness. It brings together the principles of cooperative and problem-based learning, and it is said to be the most widely used and researched strategy amongst constructivist models for teaching (Herron & Nurrenbern, 1999). Cooperative learning is a student centered active learning approach that uses structured situations where a fixed small group interacts in a non competitive, non individualistic manner to accomplish a common goal. This paradigm engages students cognitively, physically, and emotionally in constructing their own knowledge and “it is an important step in changing the passive and impersonal character of many college classrooms” (Johnson, Johnson, & Smith, 1991). It differs from collaborative work in that it is generally long term and more formal and structured (Bowen, 2000; Cooper, 1995), and students have specific roles (i.e. team leader, record keeper, etc.) (Cooper, 2009). The effectiveness of this learning strategy in producing higher achievement, more positive student attitudes and higher retention rates is supported by hundreds of studies (Johnson et al., 1991) and at least two meta-analyses (Bowen, 2000; Qin & Johnson, 1995; Springer & Stanne, 1999). In problem-based learning students are initially given a scenario or situation that motivates the need for research. The creation of
this authentic task or goal promotes discussion amongst team members and induces self-directed learning; participants are responsible for gathering, evaluating and sorting information, planning solution paths, monitor progress, and evaluate processes and outcomes. The instructor takes the role of a facilitator, a kind of guiding consultant that can be accessed as source of information but not as a source of answers to the problem itself. Instructors model the higher order thinking necessary to succeed in problem-solving and refrain from expressing opinions or giving straight answers to students’ questions. Their interactions with students should be conducted at a metacognitive level; in this interaction mode, instructors challenge learners to reflect and think thereby favoring deep understanding (Savery & Thomas, 2001). In this sense, problem-based learning is assumed to mediate metacognitive development.

Johnson and collaborators (Johnson et al., 1991) described five basic components of cooperative learning: positive interdependence, face-to-face interaction, individual accountability, interpersonal skills and group processing. Two of these aspects are of prime relevance in terms of metacognitive instruction: social interaction and group processing. Okita, Bailenson, and Schwartz (Okita, Bailenson, & Schwartz, 2007) recently reported that the mere belief one is interacting with another person led to superior learning and hypothesized that it is the participation in socially relevant actions that promotes this favorable effect. In her study of metacognition development of children in a collaborative environment, Larkin summarized the impact of social interaction by saying that: “Asking questions of oneself can begin by being questioned by others.” (Larkin, 2006). Group processing is precisely a description of collective
reflection in which the members of the team are engaged in analyzing their actions, decisions and outcomes (Johnson et al., 1991). It is in this context that the exercising of metacognitive skills such as reflective discussion, verbalization, think aloud, group planning, monitoring and evaluating takes place. Cooperative work project based laboratory instruction is one of the many possible ways to operationalizing cooperative learning (Cooper, 2009); it was implemented in the General Chemistry Program at Clemson University in 1994-1995 and since then it has served 1400-1600 students per semester. This laboratory course was designed as an environment for students to practice higher order thinking, and to develop and apply problem-solving skills in situations that resemble scientific research processes (Cooper & Kerns, 2006). It has been successfully used and has proven to be particularly effective in improving females’ achievement and retention rates (Cooper, 1994).

Even though there is a widespread acceptance of the cooperative problem-based laboratory as a metacognitive promoting strategy, there is no previous research specifically addressing the effectiveness in achieving such goals. In a related study, Larkin (Larkin, 2006) demonstrated the positive impact of collaborative work on 5-year old children’s development of metacognitive abilities. The children in this study were first year students participating of the Cognitive Acceleration through Science Education Program (CASE@KS1) in England (King's College London, 2008). In her study, Larkin used a case study approached in which the group interactions of two children were observed in nine different instances over a period of nine months as the group worked on metacognition promoting activities. The children showed steady development of their
metacognition which became progressively overt. Even though the context of Larkin’s study is substantially different from that of college chemistry, it provides relevant insight in the study of the centrality of collaborative work in the developing and/or exercising of metacognitive skillfulness. These findings offer evidence that supports that metacognition use can be influenced by social interaction and persuasion.

Cooper and her research group (E. Case, Stevens, & Cooper, 2007; Cooper, Cox, Nammouz, Case, & Stevens, 2008) used a different approach to study the effect of collaborative grouping on college chemistry students’ ability to solve online chemistry IMMEX problems. Since this particular online problem space design requires metacognitive skillfulness, the ability to solve the problem is a measure of the deployment of metacognitive skills. Under this premise, and based on supporting evidence like that contributed by Larkin (Larkin, 2006) it can be argued that group collaboration would improve individual ability through development of metacognition. Using a pretest-intervention-posttest design, Cooper and collaborators observed, indeed, a statistically significant increase in ability (typically around 10%) as result of pairing students in the problem-solving intervention. The same research group has reported similar results using a different metacognition promoting intervention: concept mapping (Cooper, Cox, Nammouz, & Stevens, 2007; Cooper et al., 2008).

These studies contribute convincing evidence showing that engaging students in metacognition eliciting environments enhances their performance in metacognition requiring tasks. Put in a different way, students can be elevated to high order thinking levels through instruction in appropriate metacognition eliciting learning environments. It
is of utmost relevance to emphasize that no study was found in which metacognition use change was assessed. The ability to bring in this factor would make the argument of metacognition development even more significant and more robust.

**Conclusion**

This chapter provided an overview of the pertinent literature in the fields of metacognition, methodologies for its assessment, and instruction techniques to promote its use and development. It also presented work that overlaps the fields of chemical education research and metacognition.

Metacognitive skillfulness is widely deemed as necessary to achieve deeper understanding and to evolve into an autonomous learner; nevertheless advancement in its assessment does not match this acceptance. This lack of adequate assessment, caused primarily by the inherent difficulties of measuring a non-overt construct, has also limited the assessment of the effectiveness of metacognitive instruction. There is a tacit assumption that making metacognitive learning environments available does develop metacognition use in students. However, there is no direct evidence for this assumption.

The following two chapters will describe the design and validation of the multimethod assessment of metacognition. Chapter Three addresses the prospective instrument, the Metacognitive Activities Inventory, while Chapter Four describes the concurrent instrument, IMMEX, and the convergence between the two individual instruments.
CHAPTER THREE

METACOGNITIVE ACTIVITIES INVENTORY, MCA-I

Introduction

As previously discussed, articles praising the relevance of metacognition in learning and problem-solving are abundant. Despite the efforts to raise awareness about and promote instruction and use of metacognition, work in developing its assessment has not paralleled this interest (Veenman, 2005) and there is a current need for instruments to measure metacognition and related constructs (Sperling et al., 2002). The intrinsic difficulties in characterizing individual’s patterns of thought and strategy development might be the cause for such gap. Additionally, assessment has seldom been tested in college science courses. College instructors interested in facilitating metacognition in the classroom, would benefit from having an adequate assessment instrument to determine changes in the use of metacognitive skillfulness (Sperling et al., 2002).

Methods like think-aloud protocols, systematic observations, and analysis of note-taking have traditionally dominated the concurrent assessment of metacognition in science. However, these are very time consuming, require individual evaluation of participants which leads to small samples, and may generate environments that are not always naturalistic and therefore may alter students’ behavior. Non concurrent procedures such as questionnaires and inventories allow a rapid assessment of a large number of participants but are questioned since they do not assess the deployment of skillfulness but rather the recollection or predictive ability of the participants, and are subject to multiple confounding factors. From this perspective, questionnaires and
inventories are second order assessments of the construct. Even though these and other problematic issues such as selection of a reference point, and social desirability, do not render this kind of instrument useless, they present a major challenge for the robustness of the assessment. As a solution to circumvent these drawbacks, the use of methodologies that utilize more than one instrument (multimethods) has been proposed (Veenman, 2005). This work describes the design and validation of an across-method-and-time assessment of metacognitive activities use in chemistry problem-solving.

By using an across-method and across-time design, construct validity is tested not only in terms of using different methods but also by collecting data at different times. Convergence between instruments reduces the reported shortcomings of self-report designs and contributes to eliminate the time limitation of traditional online assessments. The first method proposed for this work consists of a self-report instrument that can be administered and analyzed easily and rapidly at any time during the instructional cycle. The second component is an online method that tests students’ metacognitive skills using readily available technology for rapid collection and analysis of a large number of performances and will be presented in Chapter Four.

This chapter reports the development of the first instrument: the Metacognitive Activities Inventory, MCA-I. This inventory was designed to investigate what the students normally do when solving problems (metacognitive skillfulness) rather than what they claim to know about problem-solving (metacognitive knowledge). This focus on the regulation of cognition component is depicted in Figure 3.1. In reporting the
development of the instrument, the work presented here discusses the MCA-I design, reliability, validity evidence, and its structure.

Figure 3.1: Focus of the Metacognitive Activities Inventory, MCA-I

Inventory Design

Two factors are of crucial importance in constructing psychometric instruments: reliability and validity. Reliability is an estimate of consistency and reproducibility of the results generated by using a given instrument and procedure. When using educational data, use of standard error to evaluate reliability is not practical since subjecting participants to the same assessment multiple times is not feasible. Alternate ways to assess reliability have been developed, for example: test-retest, parallel testing, and single-test administration procedures (Ravid, 2005). The most often used estimate, internal consistency reliability, uses a single administration and compares the sum of the variances of the individual items to the variance of the sum scores for the individual participants. It may be understood as an index that describes how much of a measurement
is not caused by random erroneous contributions (StatSoft, April, 2008); therefore, higher values are indicative of more reliable instruments. It is commonly expressed as the Cronbach’s alpha coefficient and values above .70 are desired.

The validity of an instrument refers to the extent in which it effectively measures the construct for which it was designed (Angoff, 1988; Thorndike, 2005) and its usefulness for the proposed goal (American Educational Research Association, 1999). The main sources of validity to be considered here are construct validity, and criterion-related validity. Construct validity is the extent in which the test provides accurate information about the concept or theory being assessed. Evidence for construct validity can be determined by the ability to predict differences in groups that according to the theoretical framework ought to be different. Criterion related validity is comprised of face validity—that is, acceptability and reasonableness of the instrument to those being tested—and predictive validity, in which performance in a task or criterion is compared to the results of the test.

Another aspect of interest when designing inventories is their internal structure (Howard et al., 2000; Thorndike, 2005). It refers to the relationship among the items composing the instrument and it allows them to be classified into groups or factors. These factors can be identified based on the pattern of the responses from the participants by using statistical methods like factor analysis (Manly, B. F. J., 1994). Through this analysis, items that bear a relationship group together in separate factors, thereby providing information on the internal structure of the data. By identifying these underlying factors or dimensions, factor analysis condenses the information contained in
the original number of variables into a reduced number, thereby making interpretation and use more manageable. This is a common application of factor analysis: simplification of scales. Dimensions of a psychometric scale may represent a trait or aspect of a construct. Thorough inspection of the items within a factor facilitates uncovering this internal structure and ideally, subscales can be devised that look at specific aspect of the construct. For example, in the present study, items could group in factors ascribed to the main components of regulatory skills: planning, monitoring and evaluating. In spite of being a very powerful tool in many instances, factor analysis relies on content interpretation of variables and their relationship often making internal structure not discernible (Manly, B. F. J., 1994).

For the construction of the Metacognitive Activities Inventory, an initial pool of items was obtained using a panel-of-experts technique (four faculty members and four graduate students) (Misiti Jr., Frank L., Shrigley, & Hanson, 1991). Each expert was asked to list ten activities or skills they deemed related to successful problem-solving. Contributions were rewritten according to the commonly accepted rules for item design (Thorndike, 2005) and repeated items were omitted. About a third of the items were coded inversely to prevent acquiescence (the tendency of respondents to agree with most of the statements presented to them). Inversely or negatively coding of an item implies that it prompts a negative aspect of the construct under study, and does not refer to the syntax of the sentence. In order to collect construct validity evidence, the items were then analyzed by members of the research team (three chemical education graduate students and a faculty member with more than 25 years of teaching and research experience) and
submitted to an expert in Educational Psychology for scrutiny. The main criterion was to assure that the content matched the working definition used for metacognition which in turn had been discussed with all members of the panel. All the items utilized are exemplars of the trait described as regulatory skillfulness and conform to the theory espoused in the introductory chapters. However, attempts to classify the items as pertaining to only one of the main subcategories of planning, monitoring and evaluating were not successful. Members of the panel did not agree entirely on the classification or assigned several items to more than one subcategory. This is not surprising since the high interdependency of metacognitive skills may cause some items to fit in more than one subcategory (Veenman et al., 2005). This occurrence is in accordance with previous findings which have reported the difficulty of using factor analysis to make the structure of metacognition surface beyond its main components: knowledge and regulation of cognition (Schraw & Dennison, 1994; Sperling et al., 2002).

The preliminary version of the inventory was composed of 53 items. Agreement with each item was indicated by selecting from a 5-point Likert scale (1, strongly disagree to 5, strongly agree). Since negatively coded items probed a negative aspect of metacognition, these responses were inverted before the subsequent statistical analyses (for example, a “1, strongly disagree” becomes a “5, strongly agree”, and so forth.). All statistical analyses were performed using SPSS 14.0.

Twenty nine chemistry graduate teaching assistants and 20 seniors participated in the preliminary test data collection. Next, items were pilot-tested on a group of 151 General Chemistry students. These, as all other participants in this study, were enrolled in
a southeastern research university and signed informed consent forms to take part in the research study. Up to this point, participants were asked to comment on clarity and any other aspect they considered relevant, therefore giving an opportunity to assess and improve face validity. Analysis of item variability and extreme mean scores were used to evaluate their appropriateness. The discriminating ability of an item is deemed to be insufficient when most of the respondents agree (or disagree) with it making the item useless for the inventory (StatSoft, April, 2008). The final selection of items was based on two criteria: individual item correlation with the sum score, and the effect on Cronbach’s coefficient alpha when the item was dropped. If the individual values for a given item do not correlate strongly with the sum scores, that item is not contributing significantly to the assessment of the construct. Likewise, if the reliability increases when responses to an item are not used for the calculation of Cronbach’s coefficient alpha, then it can be safely assumed that the item is not consistent with the rest of the inventory and may be excluded. The final version of the inventory consisting of 27 items, eight of which are coded negatively, is shown in Table 3.1. In order to detect participants who might have marked answers randomly, a verification item was inserted in the instrument. This kind of item requires students to choose a specific option; the assumption is that those who fail to follow the directions are not fully engaged in responding and therefore their inventories can be excluded. Testing using freshmen, seniors and graduate students allowed analysis of construct validity since these groups were expected to give different results. Scores are reported as a percentage of the maximum attainable number of points,
MCA-I %; therefore, a higher percentage score indicates a more self-reported metacognitive individual.

**Table 3.1: Metacognitive Activities Inventory**

<table>
<thead>
<tr>
<th>Item</th>
<th>Coding</th>
<th>Statement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+</td>
<td>I read the statement of a problem carefully to fully understand it and determine what the goal is.</td>
</tr>
<tr>
<td>2</td>
<td>+</td>
<td>When I do assigned problems, I try to learn more about the concepts so that I can apply this knowledge to test problems.</td>
</tr>
<tr>
<td>3</td>
<td>+</td>
<td>I sort the information in the statement and determine what is relevant.</td>
</tr>
<tr>
<td>4</td>
<td>+</td>
<td>Once a result is obtained, I check to see that it agrees with what I expected.</td>
</tr>
<tr>
<td>5</td>
<td>+</td>
<td>I try to relate unfamiliar problems with previous situations or problems solved.</td>
</tr>
<tr>
<td>6</td>
<td>+</td>
<td>I try to determine the form in which the answer or product will be expressed.</td>
</tr>
<tr>
<td>7</td>
<td>+</td>
<td>If a problem involves several calculations, I make those calculations separately and check the intermediate results.</td>
</tr>
<tr>
<td>8</td>
<td>+</td>
<td>I clearly identify the goal of a problem (the unknown variable to solve for or the concept to be defined) before attempting a solution.</td>
</tr>
<tr>
<td>9</td>
<td>+</td>
<td>I consider what information needed might not be given in the statement of the problem.</td>
</tr>
</tbody>
</table>
Table 3.1: Metacognitive Activities Inventory *(continued)*

<table>
<thead>
<tr>
<th>Item</th>
<th>Coding</th>
<th>Statement</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>+</td>
<td>I try to double-check everything: my understanding of the problem, calculations, units, etc.</td>
</tr>
<tr>
<td>11</td>
<td>+</td>
<td>I use graphic organizers (diagrams, flow-charts, etc) to better understand problems.</td>
</tr>
<tr>
<td>12</td>
<td>+</td>
<td>I experience moments of insight or creativity while solving problems.</td>
</tr>
<tr>
<td>13</td>
<td>+</td>
<td>I jot down things I know that might help me solve a problem, before attempting a solution.</td>
</tr>
<tr>
<td>14</td>
<td>+</td>
<td>I find important relations amongst the quantities, factors or concepts involved before trying a solution.</td>
</tr>
<tr>
<td>15</td>
<td>+</td>
<td>I make sure that my solution actually answers the question.</td>
</tr>
<tr>
<td>16</td>
<td>+</td>
<td>I plan how to solve a problem before I actually start solving it (even if it is a brief mental plan).</td>
</tr>
<tr>
<td>17</td>
<td>+</td>
<td>I reflect upon things I know that are relevant to a problem.</td>
</tr>
<tr>
<td>18</td>
<td>+</td>
<td>I analyze the steps of my plan and the appropriateness of each step.</td>
</tr>
<tr>
<td>19</td>
<td>+</td>
<td>I attempt to break down the problem to find the starting point.</td>
</tr>
<tr>
<td>20</td>
<td>-</td>
<td>I spend little time on problems for which I do not already have a set of solving rules or that I have not been taught before.</td>
</tr>
<tr>
<td>21</td>
<td>-</td>
<td>When I solve problems, I omit thinking of concepts before attempting a solution.</td>
</tr>
<tr>
<td>22</td>
<td>-</td>
<td>Once I know how to solve a type of problem, I put no more time in understanding the concepts involved.</td>
</tr>
<tr>
<td>23</td>
<td>-</td>
<td>I do not check that the answer makes sense.</td>
</tr>
</tbody>
</table>
Table 3.1: Metacognitive Activities Inventory (continued)

<table>
<thead>
<tr>
<th>Item</th>
<th>Coding</th>
<th>Statement</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>-</td>
<td>If I do not know exactly how to solve a problem, I immediately try to guess the answer</td>
</tr>
<tr>
<td>25</td>
<td>-</td>
<td>I start solving problems without having to read all the details of the statement.</td>
</tr>
<tr>
<td>26</td>
<td>-</td>
<td>I spend little time on problems I am not sure I can solve.</td>
</tr>
<tr>
<td>27</td>
<td>-</td>
<td>When practicing, if a problem takes several attempts and I cannot get it right, I get someone to do it for me and I try to memorize the procedure.</td>
</tr>
</tbody>
</table>

Validity, Reliability, and Structure of the MCA-I

Data collection

Following its design, further data collection was conducted with the inventory to complete its reliability, validity and structure analyses. The instrument was administered using the version presented in Table 3.1 and again a 5-point Likert scale. Data gathering was divided into two stages: main and replication studies. The studies were conducted over two consecutive semesters, and as stated previously, all students involved in this project signed informed consent forms. Participants in the main study were 310 students enrolled in 15 laboratory sections of General Chemistry 1. The replication study was conducted in General Chemistry 1 the semester immediately after the main study with 609 first year students distributed in 32 laboratory sections, additionally, 26 first year graduate students participated at this stage. As before, participants were assigned identification numbers. During the main study the instrument was administered twice: the
first administration, or pretest, was conducted during the first week of laboratory; the second administration, or posttest, was performed during check out, 13 weeks later. The instrument included written instructions; in addition, an instructor informed the students about the objective of the inventory and reminded that the researchers were interested in their usual behavior and not on that of a hypothetical or ideal student. Completion of the instrument took around 15 minutes. Incomplete inventories and those in which the verification item was wrong were discarded. The pretest responses were collected online by using a web version of the instrument. From a total of 310 submitted responses, 290 were adequately completed and used for the study. Hard copies and optical reader answer sheets were employed for the posttest. A total of 280 inventories were useful for the study. The number of participants identified as having been tested in both administrations was 235, the main cause for this drop being failure to correctly enter the assigned identification number. All responses for both the pre (609 students) and posttest (605 students) in the replication study were collected using optical reader answer sheets. A total of 537 participants successfully completed both tests. Analysis of variance and scale descriptive statistical analyses were performed using SPSS 14.0.

Results

Table 3.2 presents the results for the administration of the instrument during the main and the replication studies. According to the paired t-test for the main study (235 participants), pre and post MCA-I scores were not significantly different at the .05 level. The Pearson’s correlation coefficient for these two administrations is .53 and significant at the .01 level. Consistent results were obtained for the replication study: paired t-test p-
value of .07 (537 participants), Pearson’s correlation coefficient for pre and post administration of .51 and significant at the .01 level.

Table 3.2: Scores and Reliability for the MCA-I Administrations, General Chemistry

<table>
<thead>
<tr>
<th>Administration (n)</th>
<th>MCA-I %</th>
<th>α</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main study</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pretest (290)</td>
<td>75.0</td>
<td>.85</td>
</tr>
<tr>
<td>Posttest (280)</td>
<td>73.4</td>
<td>.92</td>
</tr>
<tr>
<td>Replication</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pretest (609)</td>
<td>76.0</td>
<td>.87</td>
</tr>
<tr>
<td>Posttest (605)</td>
<td>75.2</td>
<td>.91</td>
</tr>
</tbody>
</table>

Analysis of variance for the main study pretest mean MCA-I values by course letter grade showed that only the A group was significantly different from all others at the .05 level (Table 3.3). Students who received an F were not considered for this analysis since their number was too small and usually a wide range of factors contribute to students failing a course. Correlation between MCA-I score and overall GPA for this same group, main study pretest, was significant with a p-value of .015, though the Pearson’s correlation coefficient was not particularly large (.16).
Table 3.3: First Administration MCA-I Mean Scores by Letter Grade

<table>
<thead>
<tr>
<th>Grade (N)</th>
<th>MCA-I mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>D (21)</td>
<td>71.8</td>
</tr>
<tr>
<td>C (56)</td>
<td>73.3</td>
</tr>
<tr>
<td>B (73)</td>
<td>74.1</td>
</tr>
<tr>
<td>A (71)</td>
<td>77.3</td>
</tr>
</tbody>
</table>

Figure 3.2 shows the proportion of participants in the top (high), middle (medium) and bottom (low) third of the MCA-I scores (pretest, main study) by letter grade.

Figure 3.2: MCA-I Score Distribution for Chemistry 1 Letter Grades
Table 3.4 shows the scores and reliability values corresponding to the administration of the MCA-I to graduate students during the preliminary and replication tests. Analysis of variance showed that in both cases, the mean value for the graduate students was significantly higher than that for the undergraduate student participants in the main study at the .05 level (p-values < .02).

Table 3.4: Scores and Reliability for the MCA-I Administrations, Graduate Students

<table>
<thead>
<tr>
<th>Administration (n)</th>
<th>MCA-I %</th>
<th>α</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preliminary (29)</td>
<td>78.5</td>
<td>.74</td>
</tr>
<tr>
<td>Replication (26)</td>
<td>80.0</td>
<td>.92</td>
</tr>
</tbody>
</table>

The MCA-I scores corresponding to the pretest and the posttest for the main study were subject to factor analyses. Adequacy of the sample for factor analysis was assessed by using the Kaiser-Meyer-Olin measure and in both administrations it was satisfactory (0.85 and 0.94). Separate exploratory unrestricted factor analyses using an orthogonal Varimax rotation with Kaiser normalization were performed independently in both cases. The first one produced a seven factor solution with eigenvalues greater than one that accounted for 51% of the total variance. Inspection of the items clustered by this method did not lead to any sensible interpretation of the structure of the instrument. Moreover, using the scree plot as criterion, a solution containing two or three factors appeared more likely to give meaningful results. Restricted solutions using four, three and two factors were performed and consistently, all of the items that were coded negatively clustered...
together while the others distributed in the remaining factors. For the four- and three-factor solutions, the factors containing the positively coded items could not be differentiated in terms of the nature of the items. Finally, the two-factor solution proved to be the most interpretable, and it resulted in 29% of the cumulative variance. Item affiliation to a factor was determined by a loading value greater than .35. Items loaded unambiguously on only one factor except for items 14 (.409 and .454) and 22 (.408 and .380), and item 16 which did not load significantly in either factor (.201 and .242), Table 3.5. The correlation between the subscales was significant at the .01 level (Pearson’s coefficient of .56) and present good internal consistency as indicated by their coefficient α (.83 and .75). Table 3.6 summarizes the results for the individual factors.
Table 3.5: Loading Factors for Both MCA-I Administrations*

<table>
<thead>
<tr>
<th>Item</th>
<th>Factor 1 Positive Subscale</th>
<th>Factor 2 Negative Subscale</th>
<th>Factor 1 Positive Subscale</th>
<th>Factor 2 Negative Subscale</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.349</td>
<td>.181</td>
<td>.755</td>
<td>.157</td>
</tr>
<tr>
<td>2</td>
<td>.569</td>
<td>.197</td>
<td>.694</td>
<td>.150</td>
</tr>
<tr>
<td>3</td>
<td>.502</td>
<td>.046</td>
<td>.789</td>
<td>.119</td>
</tr>
<tr>
<td>4</td>
<td>.446</td>
<td>.285</td>
<td>.703</td>
<td>.191</td>
</tr>
<tr>
<td>5</td>
<td>.383</td>
<td>-.074</td>
<td>.754</td>
<td>.021</td>
</tr>
<tr>
<td>6</td>
<td>.489</td>
<td>.111</td>
<td>.744</td>
<td>.092</td>
</tr>
<tr>
<td>7</td>
<td>.015</td>
<td>.486</td>
<td>.158</td>
<td>.626</td>
</tr>
<tr>
<td>8</td>
<td>.190</td>
<td>.544</td>
<td>.194</td>
<td>.587</td>
</tr>
<tr>
<td>9</td>
<td>.372</td>
<td>.086</td>
<td>.425</td>
<td>.258</td>
</tr>
<tr>
<td>10</td>
<td>.109</td>
<td>.562</td>
<td>.433</td>
<td>.515</td>
</tr>
<tr>
<td>11</td>
<td>.513</td>
<td>.347</td>
<td>.715</td>
<td>.272</td>
</tr>
<tr>
<td>12</td>
<td>.145</td>
<td>.624</td>
<td>.009</td>
<td>.714</td>
</tr>
<tr>
<td>13</td>
<td>.465</td>
<td>.117</td>
<td>.658</td>
<td>.054</td>
</tr>
<tr>
<td>14</td>
<td>.409</td>
<td>.454</td>
<td>.585</td>
<td>.353</td>
</tr>
<tr>
<td>15</td>
<td>.037</td>
<td>.681</td>
<td>.028</td>
<td>.645</td>
</tr>
<tr>
<td>16</td>
<td>.201</td>
<td>.242</td>
<td>.508</td>
<td>.005</td>
</tr>
<tr>
<td>17</td>
<td>.453</td>
<td>-.028</td>
<td>.587</td>
<td>-.075</td>
</tr>
<tr>
<td>18</td>
<td>.529</td>
<td>.174</td>
<td>.672</td>
<td>.085</td>
</tr>
<tr>
<td>19</td>
<td>.255</td>
<td>.417</td>
<td>.263</td>
<td>.560</td>
</tr>
<tr>
<td>20</td>
<td>.136</td>
<td>.591</td>
<td>.015</td>
<td>.507</td>
</tr>
<tr>
<td>21</td>
<td>.592</td>
<td>.138</td>
<td>.631</td>
<td>.209</td>
</tr>
<tr>
<td>22</td>
<td>.408</td>
<td>.380</td>
<td>.703</td>
<td>.332</td>
</tr>
<tr>
<td>23</td>
<td>.443</td>
<td>.222</td>
<td>.697</td>
<td>.185</td>
</tr>
<tr>
<td>24</td>
<td>.634</td>
<td>.141</td>
<td>.710</td>
<td>.130</td>
</tr>
<tr>
<td>25</td>
<td>.557</td>
<td>.104</td>
<td>.614</td>
<td>.269</td>
</tr>
<tr>
<td>26</td>
<td>.489</td>
<td>.220</td>
<td>.642</td>
<td>.166</td>
</tr>
<tr>
<td>27</td>
<td>.012</td>
<td>.568</td>
<td>.063</td>
<td>.557</td>
</tr>
</tbody>
</table>

* Affiliation indicated by highlighting of value
Table 3.6: Comparison of Factors for MCA-I Administrations

<table>
<thead>
<tr>
<th>Scale</th>
<th>Initial administration</th>
<th>Final administration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Score (%)</td>
<td>α</td>
</tr>
<tr>
<td>Factor 1 Positive Subscale</td>
<td>78.0</td>
<td>.83</td>
</tr>
<tr>
<td>Factor 2 Negative Subscale</td>
<td>70.0</td>
<td>.75</td>
</tr>
<tr>
<td>MCA</td>
<td>75.0</td>
<td>.85</td>
</tr>
</tbody>
</table>

The main study posttest replicated the factor analysis for the corresponding pretest. Unrestricted factor analysis resulted in a solution with four components having eigenvalues greater than one. However, once again, factor interpretation was not suitable, and the scree plot was consistent with a two- or three-factor solution. Four-, three- and two-factor analyses were performed, this time with the additional objective of comparing them with those for the first administration. As before, consistent clustering of the negatively coded items was observed while the other items arranged themselves in the remaining factors, resembling very closely the results obtained for the previous administration, although not identical. This time, the two-factor solution accounted for 46% of the cumulative variance and was completely unambiguous: all of the items but one loaded greater than .5 on a single factor (Table 3.5). The subscales were strongly correlated (Pearson’s coefficient of .45, significant at the .01 level), and reliable with coefficients α of .93 and .76 (Table 3.6).

Considering the results for the second administration, items 14, 16 and 22 were confidently and conclusively assigned to Factor 1. Since the first factor contains all of the
19 positively coded items, it will be referred to as the *Positive Subscale*; and the second factor grouping the eight negatively coded items, the *Negative Subscale*.

The factor analysis of the Negative Subscale for both administrations clearly suggests that it is unidimensional. In both cases, there is only one subfactor with eigenvalue greater than one and accounting for 34% and 37% of the variance, in the first and second administration, respectively. The scree plot criterion is also concordant with the presence of only one factor in both experiments.

Homogeneity of the Positive Subscale is not as clear as that for the Negative Subscale. For the second administration, the Positive Subscale shows three subfactors with eigenvalues greater than one which account for 59% of the total variance. The three subfactors obtained have good reliability considering the number of items associated with each one (Table 3.7) and are significantly correlated at the .01 level with Pearson’s coefficients of .57, .66 and .76. Thirteen out of the 19 items loaded unambiguously on only one subfactor. Results for the pretest analysis were similar though there was significant shifting in the item loading.

**Table 3.7: Factor Analysis of the Positive Subscale, Posttest**

<table>
<thead>
<tr>
<th>Subfactor</th>
<th>Number of items</th>
<th>Average score (%)</th>
<th>α</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
<td>77.81</td>
<td>.93</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>73.49</td>
<td>.77</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>72.12</td>
<td>.70</td>
</tr>
</tbody>
</table>
Figure 3.3 shows the scree plot corresponding to the Positive Subscale, second administration.

![Figure 3.3: Positive Subscale Scree Plot, 2nd Administration](image)

**Discussion**

The main purpose of this study was to develop and validate a short, easy to use, self-report instrument of high quality to assess the use of metacognition in chemistry problem-solving. The first issue addressed was the reliability. Estimates obtained from single administration of the instrument conveyed evidence of high reliability as shown by the Cronbach’s coefficient α values in Table 3.2 (all values ≥ .85). Single administration reliability evidence was supported by retesting after a 13 week interval. The scores for the two administrations during the main study were not significantly different (p-value > .05), and were highly correlated (Pearson’s coefficient .53, significant at .01 level). The single administration and test/retest procedures employed to extract reliability evidence cover all the common sources of variation in an individual’s usual performance
(Thorndike, 2005), and clearly support the claim of a consistent and reproducible measurement. The administration of the inventory to an independent cohort during the replication study contributes to reliability evidence by its consistently high coefficient $\alpha$ (Table 3.2). Robustness of the inventory is supported by the high correlation between the two administrations during this second study (Pearson’s coefficient .51, significant at the .01 level). The smaller Cronbach’s coefficient $\alpha$ observed for graduate students may be due to the smaller sample size and the smaller variability expected within this quasi-expert group (Table 3.4).

The second aspect under scrutiny was validity. Validity describes the extent in which theory and experimental evidence support the intended use of test results (Angoff, 1988; Thorndike, 2005). In the case of the MCA inventory, the items describe behaviors used as indicators of the construct under study. These behaviors include planning, monitoring and evaluating as components of the regulation of cognition. Although the difference might be subtle in some cases, the instrument developed looks at what the students declare that they do normally when solving problems and not at what they claim to know about problem-solving. To illustrate this difference one item from the MCA-I, “I analyze the steps of my plan and the appropriateness of each step”, can be compared to a published knowledge of cognition item, “I am good at organizing information” (Schraw & Dennison, 1994). Very clearly, the former describes a conscious path of action, whereas the latter sheds light upon a reflection about one’s abilities. Of course, participants must be aware of their do’s and do not’s to be able to report their usual performance. However, metacognitive knowledge does not necessarily imply execution
of the metacognitive skill (Veenman et al., 2005). Item construction stressed the emphasis on metacognitive skillfulness right from the start when the collaborating experts were specifically asked to identify processes and activities desirable in chemistry problem-solving. In most cases indeed, the suggested activities fell clearly within the regulatory skills as considered in light of the theoretical framework. All the scale items are exemplars of the trait described as regulatory skillfulness, as confirmed by the Psychology Education expert. That is: they conformed to the theory espoused in the design validates the content for the proposed use for the instrument. Engaging the participants in responding to the items honestly and with their best intention is indispensable to achieve data of quality. Their cooperation is in correspondence to the reasonableness of the scale appearance and to how serious and well thought the instrument seems to be. Being this an aspect grounded on perception, it was evaluated during the preliminary testing by asking students to contribute comments and observations about the intelligibility and clarity. Students were also given space to make comments on any other regard they considered necessary. It was concluded that after implementing changes derived from these observations, the needs for face validity were fulfilled.

The use of academic achievement as evidence of construct validity for metacognition is not always warranted (Sperling et al., 2002). The correlation between the MCA-I mean scores for the main study pretest and GPA was low (Pearson’s coefficient of .16) yet significant (p-value = .015, N = 231). Even though high regulatory skillfulness can be thought of as a facilitator for learning and academic achievement, its
reflection on grades is significant only if the assessment is based on complex high level thinking that elicits and unmask metacognitive differences in the participants. The assessment for the course was based on multiple choice tests which do not necessarily fulfill these characteristics. Previous evidence suggests that metacognitive ability is a good predictor in ill-structured problem-solving but not necessarily so in well-structured problem performance (Hong, McGee, & Howard, 2000). Still, even if the task is not metacognitively discriminating, it can be argued that more metacognitive subjects may be able to develop more effective strategies for multiple-choice test taking. For instance, they may realize that this kind of assessment is based on recognition of the right answer more than actually recalling pertinent information (Schraw et al., 2005). As more metacognitive learners, they can adjust their studying and test taking strategies to perform better for a task that is not so metacognitively demanding. This finding might be used with discretion as evidence of construct validity. These results agree with literature reporting high metacognition use resulting in high performance even though the typical correlation values are low (O'Neil Jr. & Abedi, 1996), and fit with the argument of proponents of metacognition as one of the three factors determinants of success in learning and performing, the other two being cognition and motivation (Schraw et al., 2005).

The distribution of the main study pretest MCA-I mean scores by letter grade (Table 3.3) shows a trend consistent with more metacognitive students earning a higher grade. Letter grade A students MCA-I average is significantly different from the others’. Students who received an F in the course were not included in the analysis since the small
number in this category \((n = 9)\) would make the mean disproportionately subject to individual scores. Another way to look at these results is depicted in Figure 3.2, in which three MCA-I bands have been created by splitting the scores into the high, medium and low thirds. The proportion of high-metacognition users is larger for higher grades, and correspondingly, more low-metacognition users populate the lower letter grades. However, students falling in the three MCA-I score-bands were found across all letter grades, thereby supporting the observation that achievement and course success are complex and not determined by a single variable. Although metacognitive strategies can be used to improve student performance and achievement, the importance of motivational and cognitive factors and the interactions among them must be acknowledged (Mayer, 2001). Factors such as task appeal, lack of necessary domain-specific knowledge (Veenman et al., 2005), motivation and the nature and format of the test questions have a decisive influence on the use of metacognition.

Another argument for validity of the MCA-I scale is the ability to differentiate between groups that should possess different levels of the characteristic under study. It seems reasonable to expect regulatory skillfulness to increase as expertise within a domain increases (Georghiades, 2000) and findings in which individuals with higher education levels exhibited higher levels of metacognition support this claim (O'Neil Jr. & Abedi, 1996). Consistent with this suggestion, Tables 3.2 and 3.4 show that the mean scores for the graduate students (preliminary and replication studies, 78.5% and 80.0%, respectively, Table 3.4) were significantly higher (all p-values < .02) than those for General Chemistry students (mean values ranging from 73.4% to 76.0%, Table 3.2)
Prevention of acquiescence requires statements with which respondents in both extremes of the trait measured would agree. Consistent with the construct validity approach, it was predicted that the positive and negatively coded items would be inversely correlated. It must be emphasized that in the process of calculating the sum score, the scoring for the negatively stated items is inverted so that all item scores directly describe metacognitive skillfulness. Evidence supported the expected behavior: The Negative Subscale containing the inverted scores for the negatively coded items and the Positive Subscale were significantly correlated at the .01 level with Pearson’s coefficient of .56 and .46 for the pretest and posttest administrations, respectively. This direct correlation of the subscales implies the inverse correlation for the oppositely coded item groups.

The third issue addressed was scale structure. In previous studies, the use of factor analysis to elucidate the multidimensional structure of metacognition has only been partially successful (Schraw & Dennison, 1994; Sperling et al., 2002). Schraw observed that unrestricted factor analysis did not correspond with the number of factors expected, neither was the constitution of them close to that presumed during the design stage. However, in his case, a two-factor restricted analysis led to readily interpretable subscales which corresponded to the main components of metacognition: knowledge of cognition and regulation of cognition. Similarly, in the present study, unrestricted factor analysis did not shed light on multidimensional structure. The MCA-I was designed to contained items of only one of the dimensions identified by Schraw—the regulatory skillfulness—therefore, its one dimensionality is seen in completely coherent with this previous report.
The results of the factor analysis fully corroborate the experience faced by the research team during item design when categorization into the three subcomponents (planning, monitoring, and evaluating) proved to be not practical.

Throughout the restricted analyses, all eight negatively coded items grouped together which was very much expected. As written, these items represent activities that negatively affect problem-solving, whereas the remaining 19 positively coded items constitute a dimension with positive influence. These two subscales measure opposites as indicated by their inverse correlation, and are useful to evaluate the reliability of an individual’s answers to the overall scale. Robustness and stability of the instrument is reflected by the almost identical affiliation of items for both administrations as depicted in Table 3.5. As mentioned above, the subscales are of good reliability as indicated by the coefficients $\alpha$ shown in Table 3.6.

Factor analysis of the Negative Subscale proved it to be unambiguously homogeneous: only one factor surfaced during the analysis of both administrations. Content analysis of the items in the three subfactors obtained for the Positive Subscale (Table 3.7) indicates that, to some extent, they are grouped according to the regulatory dimensions considered during design: planning, monitoring and evaluating. However, there is little resemblance between the item subfactor affiliations between the two administrations. This is not surprising as consequence of the high correlation between the subfactors which inevitably leads to high shifting of the items amongst them. The high interdependency of metacognitive skills has been cited before (Veenman et al., 2005) and the same factorial behavior was reported previously (Schraw & Dennison, 1994) for the
dimensions of regulatory skills. The scree plot for the Positive Subscale in both analyses was, for practical purposes, identical. Figure 3.3 shows the one corresponding to the posttest administration. This graphical criterion clearly indicates the presence of a single dimension for this subscale. It has been reported that in some instances, the Kaiser criterion which keeps only factors with eigenvalues larger than one, keeps too many factors whereas the scree plot criterion may keep too few (StatSoft, April, 2008). Upon these considerations, it is estimated convenient to consider the Positive Subscale as a whole instead of breaking scores into its subfactors. In summary, factor analysis did not shed light on the internal structure of the scale. Contrary to being disappointing, this effect is clearly understandable when the nature of the construct and previous studies are considered. This analysis was significant in contributing validity and robustness evidence.

**Conclusion**

Based on the findings reported in this study, the MCA-I is a robust, reliable and validated assessment of metacognition use in chemistry problem-solving. Reliability was measured in terms of internal consistency, as well as the reproducibility observed after retesting. Validity was examined in two dimensions: face validity, in terms of the acceptability and reasonableness to those who are tested; and construct validity, in the extent its items conform to the functional definition of the construct measured, its ability to predict group differences, and the inverse correlation of inversely coded items. It is estimated that the evidence gathered sufficiently supports the validity of the inventory.
In this study, the internal structure of the inventory was explored using factor analysis. However, no internal structure emerged from this analysis. As mentioned previously, this is well in accordance with previous findings and related to the high interdependency of metacognitive skills.

Metacognitive skillfulness is undoubtedly a very relevant aspect of chemistry understanding and problem-solving. Administration of the MCA-I consumes very little instructional time and allows access to valuable and insightful information that can be used at different levels. First, mean scores can be used to contrast metacognitive skillfulness of groups of students. This comparison can include groups or sections simultaneously enrolled in General Chemistry or not. Contemporary teaching is understood as a student centered process and, within the limitations that large enrollment may impose, it is essential for instructors to develop a good grasp of relevant student characteristics that may affect their success. The proposed inventory could be used as one of a group of instruments initially used to create a class profile.

Second, the MCA-I provides a means for identifying students who in comparison to the rest of the class may be classified as low metacognition users and who may benefit from appropriate interventions. Lastly, the MCA-I can be used by practitioners to evaluate the effect that changes in their teaching practice or learning environments may have on the use of metacognitive skillfulness by their pupils.

As indicated before, the Metacognitive Activities Inventory is envisioned as the first component in a multimethod instrument. The second component, IMMEX, and the utilization of the MCA-I as part of the multimethod are discussed in the next chapter.
CHAPTER FOUR

MULTIMETHOD ASSESSMENT OF METACOGNITION USE

Introduction

The previous chapter described the design, validation and characteristics of the prospective, self-report Metacognitive Activities Inventory, MCA-I. As stated in preceding chapters, this tool was envisioned as the first of two components in a multimethod instrument for the assessment of metacognition use in chemistry. This multimethod design is believed to be an effective solution to tackle the shortcomings of using individual tools separately. The drawbacks for both, non concurrent and concurrent instruments were introduced in chapters two and three. The main obstacles with traditional concurrent measures is that they are very time consuming (both at data collection and processing, and data interpretation), only a small number of participants can be analyzed, and the interpretation is prone to subjectivity causing a concern in terms of reproducibility of results. A concurrent instrument with the capability of automating the collection and processing of data as well as their interpretation would certainly circumvent these deficiencies. This chapter first introduces and describes such an instrument, the Interactive MultiMedia Exercises software, known as IMMEX, its characteristics and its application to measure metacognition use. The utility of a multimethod relies on the convergence of its components, that is, on the degree of coincidence of the results provided individually by them. Therefore a study focused on determining the convergence between the MCA-I and IMMEX is also presented in this chapter.
**Interactive MultiMedia Exercises, IMMEX**

IMMEX is a web based platform that has been described in depth (Cooper et al., 2007; Stevens & Palacio-Cayetano, 2003; Stevens, Johnson, & Soller, 2005; Underdahl, Palacio-Cayetano, & Stevens, 2001) and that has been extensively used in gathering of student performance and problem-solving strategy information (Cooper et al., 2008). Typically, an ill-defined problem is presented by using a meaningful real life type scenario. Each problem type, or *problem set*, contains multiple *cases* or *clones*. For research purposes, participants are asked to solve at least five cases of one problem set. Students are able to design their own problem-solving strategy as they navigate through the problem space analyzing and processing the information they request. The problem space contains necessary background, as well as information specific to the problem. IMMEX uses an HTML tracking feature to create a record of the items selected, their sequence and the time each item was under consideration. This information can be modeled to partially reconstruct the strategy. Artificial neural networks, ANN, and Hidden Markov Models, HMM, are used to cluster a large number of performances in a predetermined number of strategies, also called *states* (Cox, 2006; Stevens et al., 2005). Evidence indicates that for a given problem type, individuals stabilize on one state after working on five cases (E. Case, 2004; Cox, 2006; Stevens et al., 2005).

The problem selected for this work, *Hazmat*, is based on inorganic qualitative analysis and has 38 different clones (unknown substances). The prolog for Hazmat is shown in Figure 4.1. Background or *library* items contain information such as a glossary, solubility tables, flame color key, and so forth; whereas information specific to the
unknown includes tests that students can request (flame tests, precipitation tests, solubility) and physical properties. When test items are selected, students are presented with a short animation from which they can extract the result of the test. Students have then the possibility of considering their understanding and interpretation of results to continue their navigating of the environment. For instance, if a given test’s interpretation solves the identity of the anion, an efficient problem solver will most probably not request more precipitation tests. Students select those items from the problem space that they deem necessary to arrive at a solution.

Figure 4.1: Prolog for Hazmat, an IMMEX Qualitative Inorganic Analysis Problem Set
In a training phase, ANNs are fed the problem space items chosen by students (input) in a large number of performances. Based on their pattern recognition ability and self organizing capability, ANNs cluster similar performances in a set number of output nodes which then represent different approaches or strategies employed by the students. These nodes are histograms that describe the probability (vertical axis) of a given item (horizontal axis) to be chosen in a given strategy type. Figure 4.2 illustrates a single output node obtained from the ANN analysis. For the sake of simplicity, the labels for individual items are omitted and instead types of items are described and color coded.

![Sample Neural Network Node](image)

**Figure 4.2: Sample Neural Network Node**
It has been found that a total of 36 nodes are adequate for most IMMEX problem sets (Cox, 2006; Stevens, Soller, Cooper, & Sprang, 2004). This analysis produces a topological map, Figure 4.3, in which geometric distance acts as a metaphor for similarity between strategies. For instance, nodes in the upper right corner of Figure 4.3 represent strategies where the number of items selected is very high, whereas nodes in the bottom left corner show a much more discerning item selection. Once appropriately trained, the ANNs learn to identify new performances and place them in the node that best fits their strategy.

Figure 4.3: ANN Topological Map
States are reached through HMM analysis, and can be seen as clusters of nodes that emerge as related strategies. Based on thousands of performances, five states have been identified for Hazmat; Figure 4.4 shows the ANN nodes related to each of these five states which are also color coded in Figure 4.3. The probability of individuals to move away from the states (probability of transition) is shown in Figure 4.4.

Figure 4.4: Hazmat Strategy States and Associated Nodes

Individual strategies or nodes can be analyzed in terms of the number of items chosen and their type (for instance, chemical tests, physical properties or library items) and relevance to the case in study. This in-depth analysis of the nodes associated with each state in conjunction with the probability of transition, allow characterization in
terms of the implied use of metacognition (Table 4.1). For example, Strategy State 1 represents participants who move rapidly to furnish an answer with little consideration of the background information and without running tests thought to be crucial by experts. Also, there is not noticeable consistency of the items chosen, suggesting random picking of information. Students in this strategy state have a high probability (p = .99) of remaining in it in subsequent cases, despite the fact that they are informed that their responses are incorrect. This strategy is associated with lack of planning skills, poor ability to sort out items based on their relevance, and poor monitoring and evaluating skills. Therefore, it is characterized as the lowest in metacognition use. At the other extreme, participants in Strategy State 5 use an adequate number of items to solve the problem, invariably choose those of high relevance (for example, flame test), consult the background information and remain in this strategy having realized it is effective and efficient (p = .95).

Table 4.1: State Descriptions for the Hazmat Problem Set

<table>
<thead>
<tr>
<th>State</th>
<th>Description</th>
<th>Strategy descriptor*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Limited, few items used.</td>
<td>L</td>
</tr>
<tr>
<td>2</td>
<td>Equal use of background and test items.</td>
<td>I</td>
</tr>
<tr>
<td>3</td>
<td>Prolific use of problem space items.</td>
<td>L</td>
</tr>
<tr>
<td>4</td>
<td>Many tests, little use of background information.</td>
<td>I</td>
</tr>
<tr>
<td>5</td>
<td>Efficient, relatively few items including relevant ones.</td>
<td>H</td>
</tr>
</tbody>
</table>

* L: low; I: intermediate; H: high.
For the purposes of this work, Strategy States 1 and 3 are classified under “low metacognition use, L” (Table 4.1). These strategies are more prevalent in the solution of the first case attempted, while the students are framing the problem. Those participants who do not move away from these states are less metacognitive. States 2 and 4 are “intermediate, I”. In the initial case, these states are not common but are populated later on by students moving specially from State 3 (with a 34% probability to State 2 and 33% probability to State 4, see Table 4.1). Careful analysis of the nodes associated with them reveals that the main difference between these two intermediate states is the nature of the information used as indicated by the space items with higher selection frequency. The relative frequency of different types of items can be seen directly from the output node, as exemplified in Figure 4.2. Strategy 2 uses about the same proportion of tests and library items, whereas Strategy 4 is data driven, with less use of background. State 5 is considered “high, H”; as pointed out above, this strategy is the most efficient.

The modeling for this particular problem set, Hazmat, has been trained with thousands of performances (Cox, 2006). In summary, participants can be readily classified into one of the three metacognition use descriptors (high, intermediate or low) based on their strategy use once they have stabilized (solved at least five cases). Since collection of data and its processing is highly automated, it is not subject to researcher’s bias. Another relevant aspect of the use of IMMEX technology as a measure of metacognition use is that even though the collection of information is concurrent with the performance of the problem, the participant is not fully aware of this happening and is not under any kind of supervision which presumably creates a more comfortable and
naturalistic problem-solving setting, thereby facilitating the natural deployment of regulatory skills.

The IMMEX performance data can also be modeled using item response theory, IRT, to obtain a second piece of valuable information: student ability (Hambleton, Swaminathan, & Rogers, 1991). This parameter can be viewed as a measure of the level of case difficulty that a given student can solve. Since not all Hazmat cases are of the same difficulty level (i.e. determining the identity of sodium chloride is considerably easier than solving nitric acid), a simple comparison of correctness might be misleading. Ability calculation considers the different difficulty of the items, hence enabling reliable comparisons of students’ performance; it uses a relative scale where higher values correspond to higher student ability. This parameter allows us to investigate the correlation with state efficiency (Cox, 2006) and MCA-I scores.

**Methodology**

All participants were students registered in the General Chemistry 1 Laboratory course, and all signed informed consent forms and were assigned identification numbers. Administration of the Metacognitive Activities Inventory, MCA-I, took place during the first week the laboratory sections met. Hard copies of the instrument were used and responses were entered on optical reader answer sheets. Typically, completion of the instrument took about 15 minutes. Incomplete inventories and those in which a verification item was wrong were discarded. The first day of laboratory, participants were informed via electronic mail of their first IMMEX Hazmat problem assignment. They were assigned to solve six cases which were due before the next laboratory meeting. A
total of 209 students completed both assessments; all others were excluded from the analysis. Hazmat data were modeled by the IMMEX Project as described previously, thereby obtaining state and ability reports for each participant. SPSS 14.0 was utilized for descriptive statistics of the inventory administration, and to run analysis of variance studies for ability and MCA-I scores by state. The same software package was used to measure the correlation between ability and MCA-I score and to conduct frequency distribution analyses.

**Results and Discussion**

Table 4.2 shows the mean values for the % MCA-I and the ability (IRT) by Hazmat strategy. For both, % MCA-I and ability (IRT), the trend is towards higher mean values for more efficient strategies, with the mean values for the high metacognitive strategy significantly different from the other two groups at the .05 level. The MCA-I and the ability (IRT) were significantly correlated at the .01 level, although the correlation coefficient is not particularly high ($r = .2$).

**Table 4.2 MCA-I and Ability by Strategy State (N = 209)**

<table>
<thead>
<tr>
<th>Strategy (n, sample %)</th>
<th>%MCA-I</th>
<th>Ability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low (45, 21.5)</td>
<td>74.1</td>
<td>43.8</td>
</tr>
<tr>
<td>Intermediate (145, 69.4)</td>
<td>75.2</td>
<td>45.5</td>
</tr>
<tr>
<td>High (19, 9.1)</td>
<td>80.7</td>
<td>49.3</td>
</tr>
<tr>
<td>Mean</td>
<td>75.5</td>
<td>45.5</td>
</tr>
</tbody>
</table>
The results of this study show that there is considerable convergence between the two instruments employed to assess metacognition use by General Chemistry students (Table 4.2). The three indicators employed, MCA-I score, ability and strategy, are in mutual agreement and in accordance with the expectations derived from the theoretical framework. Students classified as Hazmat low metacognitive strategy users had the lowest MCA-I score and showed the lowest mean ability, whereas students who used the most efficient Hazmat strategies, had statistically significantly higher corresponding measures.

It is important to emphasize that the Hazmat strategy states had been described in the literature previous to this study (Stevens et al., 2004). Even though the magnitude or strength of the relationship between MCA score and the ability is not high, one must remember that the significance of the relationship is as important in the interpretation of the results (Ott & Longnecker, 2001). The significant correlation between the ability and % MCA-I at the .01 level supports the convergence of the instruments.

A 2005 review of pivotal importance by Veenman (Veenman, 2005) concluded that “little or no correspondence between prospective and retrospective statements on the one hand, and actual, concurrent behavior on the other” was revealed. He pointed out reasons why prospective and retrospective statements may be inadequate (i.e. concerns about the reconstruction and verbalization of skills), but the overriding focus of this paper is the need for multimethod research on metacognitive skills as a source of evidence for convergent validity, that is, the agreement between scores on tests intended to assess the same construct (American Educational Research Association, 1999). The report
presented here contributes sound evidence in that direction by developing of an across-method-and-across-time design for the assessment of metacognitive skillfulness in college chemistry problem-solving. Convergence between these instruments reduces the reported shortcomings of self-report designs and eliminates the time limitation of traditional concurrent assessments.

Another significant contribution in itself is the use of available technology for the concurrent assessment of metacognition use. IMMEX allows for the collection and recording of strategy information through direct execution of metacognitive skills without interference or disturbance by the researchers. Traditional concurrent assessments usually require of environment that is not naturalistic and participants are aware of being under observation. Using IMMEX, students choose the physical environment and time to work on the problems. Other possible disadvantages of traditional methods that are removed by IMMEX are: verbalization differences, calibration of raters, inter-rater reliability issues, and the bias factor originated from researchers doing the data coding and analysis, since IMMEX performances are modeled in an automated fashion. IMMEX data collection and modeling capability allows for the investigation of hundreds or thousands of students. This potential use makes IMMEX a powerful instrument in the concurrent analysis of metacognition and related constructs.

Although, as shown, most students show convergence between self assessed metacognitive activity, and their IMMEX problem-solving strategies, there are some cases in which these two parameters do not seem to converge. As important as the cases that demonstrate convergence are, those that do not correlate may even be more
important for the designing of specific in-class interventions. In order to conduct
distribution analyses, the MCA-I scores are divided into three groups:

- a low or “L group”; those participants below the mean value minus one
  standard deviation,
- a high or “H group” participants with scores above the mean value plus
  one standard deviation,
- an intermediate or “I group” composed by those whose score is between
  these extremes.

Table 4.3 shows the possible combinations of the strategy descriptors (H, I, L as
defined in Table 4.1) and the self-reported metacognition groups H, I, L. The columns in
Table 4.3 correspond to the strategy descriptors, the rows to the metacognition groups,
and the cells represent the crosstabulation of frequency. For example, cell labeled “LL”
shows that 22.6% of the participants who self-reported as low metacognition users
performed in the low metacognition strategy group (% within MCA-I). Conversely,
15.6% of the total that performed in the low metacognition strategy group had reported to
be low metacognition users (% within state). Top figures across a row add up to 100%
(within MCA-I); bottom figures down a column add up to a 100% (within state)
Table 4.3: Combination of Strategy Levels and Self-Reported MCA-I Levels

<table>
<thead>
<tr>
<th>MCA-I group *</th>
<th>State descriptor *</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>L</td>
<td>I</td>
<td>H</td>
</tr>
<tr>
<td>L</td>
<td>LL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>% Within MCA-I</td>
<td>22.6</td>
<td>74.2</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>% Within state</td>
<td>15.6</td>
<td>15.9</td>
<td>5.3</td>
</tr>
<tr>
<td>I</td>
<td>IL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>% Within MCA-I</td>
<td>23.5</td>
<td>68.6</td>
<td>7.8</td>
</tr>
<tr>
<td></td>
<td>% Within state</td>
<td>80.0</td>
<td>72.4</td>
<td>63.2</td>
</tr>
<tr>
<td>H</td>
<td>HL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>% Within MCA-I</td>
<td>8.0</td>
<td>68.0</td>
<td>24.0</td>
</tr>
<tr>
<td></td>
<td>% Within state</td>
<td>4.4</td>
<td>11.7</td>
<td>31.6</td>
</tr>
</tbody>
</table>

* L: low; I: intermediate; H: high.

The assignment of MCA-I groups is somewhat arbitrary, and given that the distribution of the scores approaches normality, any choice of cut off points will almost inevitably lead to adjacent values being assigned to different groups. Arranging the data in this array produces nine metacognitive awareness groups which allow the identification of students who are overestimating or underestimating their problem-solving abilities. Each metacognitive group is described by two letters, the first one representing the MCA-I group, the second the strategy descriptor. The three top right cells in Table 4.3 (LI, LH, IH) correspond to underestimates (green), the bottom left cells (IL, HL, HI) to overestimates (orange) and the groups situated on the diagonal that separates these two (LL, II, HH) are concordant. This representation of the data allows teachers to identify those students whose actions do not correlate with their beliefs about what they are doing.
This kind of evidence can directly inform teachers’ practice. For example, those students who overestimate their skills may be more resistant to participation in appropriate interventions than those who are more aware of their limited skills (LL-group). Within the overestimate cells, those who believe they are highly metacognitive but according to their actual performance are low (HL-group) may display the most resistance. Students in the HL-group may be more familiar with well-defined problems (where following a sequence of pre-established steps may lead to successful performance), may have a clear strategic understanding but not efficient strategic performance, or may be easily de-motivated. One could also speculate that these students are more prone to overconfidence, and to attribute the cause of their lack of success to external factors (the problem is “tricky” or does not resemble those done in class). This analysis can be extended to students in the other overestimate groups (IL and HI)

A similar analysis could be completed for the students who underestimate their skills. Students falling in the LH-group, those who report low metacognition but were efficient solving problems online, make up a small percentage of the study (0.5%). One could venture that this underestimate of their abilities is caused by using a very rigorous reference point to reply to the inventory which may be related to their self-image. Another possibility is that students may not be good solving well-structured problems but become highly motivated and engaged when working on more complex, inquiry driven tasks.

The HH-group, students who performed efficiently having previously scored high in the MCA-I, amounts to 31.6% of the high metacognitive performing participants
(Table 4.3). It must be kept in mind that the efficient group itself is only 9% of the total sample (Table 4.2). It follows then that the HH-group constitutes only about 3% of the total participants. Knowledge of the distribution of students in these concordant and over and underestimation subgroups can assist the practitioner in the designing and implementation of interventions. In a study in which participants were paired according to their logical thinking abilities, Cooper and collaborators (Cooper et al., 2007) demonstrated that the gain in problem-solving ability derived from a group intervention was associated with group composition. In that study, the Group Assessment of Logical Thinking test (GALT-test) was used to classify students as concrete, preformal or formal thinkers, then pairs of students were formed that included all the possible combinations. These pairs underwent a collaborative intervention and their individual performance on a posttest was examined. Across the board, students increase their ability in an IMMEX problem in about 10% with one exception. Concrete student who had been paired with another concrete student showed no significant gain. On the other extreme, preformal thinkers who had had concrete partners showed the highest improvement. This work is sound evidence of the relevance of informed decisions on group composition. Using the kind of information collected from the present study, one could argue that students in the HH-group, who may be high achievers, can be used as peer leaders allowing for their modeling of strategies during group interventions. Alternative, interventions could be tuned for the different groups and these HH students could be challenged with more difficult tasks preventing them from stalling in their individual progress and from losing
motivation. This analysis of groups is an example of the diagnostic power of the multimethod instrument.

**Conclusion**

This chapter described the use of IMMEX as a concurrent metacognition assessment instrument. The advantages of using IMMEX over traditional methods are manifold: data collection and processing are automated thereby allowing for the utilization of a large number of participants; classification of participants is also automated eliminating researcher’s bias; researcher needs not to be present during student task performance minimizing disturbance and creating a better opportunity for capturing natural deployment of student metacognitive skills; and finally, automation renders the process time efficient and inexpensive since research hours use is optimized. This example of the metacognitive assessment use of IMMEX is just exploratory and can certainly be improved. One of the immediate areas of interest would be to create problem spaces specifically designed for the task of measuring general metacognition or certain aspects of the construct.

The convergence study between the two instruments, the MCA-I and IMMEX, was also discussed in this chapter. The prospective MCA-inventory consumes very little instructional time while the concurrent assessment (Hazmat) is readily available and easily fits in any General Chemistry curriculum. The access to a reliable, efficient, multimethod assessment is of great significance for practitioners. It allows rapid collection of relevant information that informs the implementation of metacognitive interventions tuned to students’ metacognitive level.
CHAPTER FIVE
COLLABORATIVE METACOGNITIVE INTERVENTION

Introduction

Chapter One made a case demonstrating the general acceptance of metacognitive skillfulness as a necessary component to achieve deeper understanding, and to help learners’ transition from a dependent learning state to becoming autonomous (Schraw et al., 2006). It also introduced the limitations presented by the lack of simple, rapid, and automated metacognition assessment tools leading to difficulties in evaluating the effectiveness of metacognitive instruction. It has often been taken as a fact that creating metacognitive instantiations leads to metacognition enhancement, but without direct evidence, this assumption is just wishful thinking. This stance was described in terms of the teaching trap that assumes that the proposed and implemented curricula necessarily equate to the learned curriculum.

Chapter Four described the design and validation of a multimethod assessment of metacognition use in chemistry problem-solving. Creating a metacognitive intervention and assessing its effectiveness is a natural follow-up of having access to this reliable measurement method. Benefits can be understood from two non excluding perspectives: First, under the assumption that metacognitive instruction leads to metacognition enhancement, findings can serve as triangulating evidence for construct validity of the multimethod instrument; second, considering that the multimethod has been sufficiently validated (Chapter Four), findings can serve the more general purpose of supporting the development of metacognition through metacognitive instruction.
According to Schraw et al. (Schraw et al., 2006) (p. 117.): “Effective science instruction must not only increase learning, but also help students develop the metacognitive skills needed to succeed at higher levels of science, and to reconstruct their conceptual knowledge and procedural strategies when necessary.”

It has been categorically asserted that “it is possible to improve knowledge, strategies, metacognition, and motivation via classroom instruction” (Francisco & Nicoll, 1998). And that a way to accomplish it is by “creating learning environments where students are allowed to explain and defend their thinking, opinions and decisions” (Tsai, 2001). Zion et al. (Zion, Michalsky, & Mevarech, 2005) maintain that “metacognitive skills development is typically fostered by asking students to reflect on and explicitly monitor their learning performance”. However, there seems to be little evidence of the concrete effects of specific instructional techniques on metacognitive skills. A clear differentiation needs to be made between instruction that fosters the use of processes associated with metacognition, reflection for instance, and the evidence for the actual development of metacognition. The assumption of gains in metacognition use occurring just because a metacognitive environment is facilitated is as valid as assuming that learning occurs whenever lecturing takes place.

Due to the lack of adequate assessment instruments it has been common practice to create learning environments that are believed to be conducive to the practice of metacognition and then look at performance or achievement parameters related with learning and efficacy in solving problems to evaluate the effectiveness of the intervention (Davis, 2003). Even though the ultimate objective of instruction is the learning outcome,
this combination of circumstances makes the access to an assessment instrument that specifically probes changes in metacognition use extraordinary useful.

This chapter describes the design of a collaborative metacognitive intervention followed by a study assessing its effectiveness utilizing the multimethod presented in Chapter Four.

**Design of the Collaborative Intervention**

The objective of the intervention was to provide an opportunity for students to engage in small group collaboration and individual work that promoted reflection about processes and products in a problem-solving situation. Listed below are the main considerations observed during the process of designing the intervention:

1. It has been asserted that metacognition guides the problem-solving process at the same time that it improves the efficiency of this goal oriented behavior. Because of this argument it was decided to implement the intervention within the framework of problem-solving. Reflection was to be promoted around a problem-solving task.

2. Cognitive imbalance was thought of as the appropriate way to engage students to purposefully work on the intervention. The shock of failure on an otherwise apparently simple task creates this understanding disequilibrium and may awake students’ curiosity and encourage them to ponder about the *why* and *how* of this occurrence. This eventual challenge in deciphering the causes of failing is used to prompt reflection. Specific details about the problems used are given later in this chapter.

3. Researchers have demonstrated that small group gains during short term collaborative tasks can effectively transfer to individual’s problem-solving strategy and
performance (Cooper et al., 2007; Cooper et al., 2008). Others have collected qualitative evidence of metacognition development during collaborative work (Larkin, 2006) and through the practice of collective metacognitive activities (J. Case et al., 2001; Georghiades, 2006). Hausmann and collaborators have extensively studied the benefits in enhancing understanding and task performance that are associated with collaboration (Hausmann, Chi, & Roy, 2004). Therefore, the core of the protocol was designed as a group activity. However, since metacognition assessment is conducted individually a single participant component was viewed as a way to help students practice those elicited skills on their own.

(4) To prevent eventual bias originating from instructor’s cueing their own expectations from the activity, their interaction with students was deliberately kept to a minimum. This concern is clearly understood when considering that assessment is based, at least partly, on students’ self-reports and that their awareness of instructor’s expectations could tarnish the results. This is an important characteristic of research interventions that is often overlooked: (un)willingly cueing students’ performance in post-testing assessments. It was decided that instructions would be contained in the intervention document and that TAs would be given a script to be read previous to the intervention (Appendix A). A research team member would supervise the laboratory room and be available to respond to questions but again, interaction was kept to a minimum and discussion of the intervention was omitted.

(5) Since the experimental design would consist of a control and a treatment group, it was thought appropriate to create an intervention which was not chemistry
related. In this way, content advantage from the treatment group was avoided. The intervention was named “Problem-Solving Activity”, which is coherent with the context of the course and legitimizes its implementing in the laboratory. It was repeatedly emphasized that its completion was part of the laboratory assignments. However, the intervention is a stand alone activity, independent of the course, and can be employed in a diverse array of learning environments. The activity does not address any chemistry specific skills; it prompts the main aspects of regulatory skillfulness common to problem-solving in general: planning, monitoring, and evaluating.

(6) Even though the term is rather ambiguous, intervention typically refers to pedagogical protocols of short duration (from a few minutes to hours). It was decided that the present intervention would be administered in three phases. A collaborative work session to be kept around a 45 minute period (Phase 1) followed by an individual component in the form of a take home assignment (Phase 2) that would be less than half the length of the first phase. This homework would be collected a week later, during the following laboratory meeting. In this same laboratory period, feedback in the form of a summary of the activity would be presented to students (Phase 3). This summary would explicitly state the objective of informing participants about the findings (most common errors, most common student opinions, and so forth) and would not take more than 10 minutes for students to analyze individually. More detailed descriptions of the intervention components will be presented later in this chapter.

All of the desired characteristics mentioned above were considered in the process of designing the intervention. Initially, literature in problem-solving was reviewed to
identify problems that had been thoroughly studied and used in research, and that could serve the purposes here stated. Three such problems were found (Davidson et al., 1995) and used without modifications. The first problem presented in the collaborative component of the intervention reads as follows:

Barbara asked me to bring her a pair of stockings from her bedroom. Unfortunately the bedroom is dark and the light is not working. I know there are black socks and brown socks in the drawer, mixed in the ratio of 4 to 5. What is the minimum number of stockings I will have to take out to make sure that I have two stockings of the same color? (Davidson et al., 1995) p. 218.

Davidson (Davidson et al., 1995) observed that children and adults alike started solving the problem by trying to use the given ratio of black to brown socks. Many arrived at absurd answers (such as 20 or 4/5) but only some of them realized the absurdity. These findings—use of irrelevant information and inadequate monitoring and evaluating skills—suggested that this kind of problem would accomplish the objective of creating cognitive imbalance.

Once the problem was selected, a series of prompts were created to induce reflection. The strategy was to first give the participants the correct answer for the problem (3 is the minimum number of socks necessary to make sure one has two stockings of the same color) which presumably would shock teams with different responses. This was followed by questions, some of which required elaboration of an answer, some were yes or no questions, and some asked subjects to select from a list of options. The complete intervention is shown in Appendix B. The author created the list of
prompts which were evaluated and improved by the research group (one faculty and two other chemistry education graduate students). The prompts were purposefully designed to be explicitly metacognitive (Davis, 2003) placing emphasis on the processes and not the products of the problem-solving instantiation. Prompts are directive meaning that they lead the participants to reflect not in general but about specific aspects, in this particular case, specific aspects of metacognition use. Twenty six such prompts were assigned to the collaborative component, Phase 1. For the individual homework task (Phase 2), students were given the option to choose one from the other two problems selected from literature (see Appendix B, Part VI), and had to address 13 prompts. Representative items used as prompts in both instances follow:

1. “Do you think your group started working on the solution having a clear understanding of the problem? (yes) (no)”
2. “Do you think that using a representation did improve/would have improved your performance? Explain briefly.”
3. “Read the following statements and mark yes, no or n.a. (not applicable):
The team answered the problem inappropriately fast.
The team used some sort of representation (drawing, diagram, flow chart, etc.)
The team devised a plan.
Was the plan complex?
Was the plan purely mental?
Was planning sufficient?

The team thinks planning is not indispensable.”

Phase 3 of the instrument presents participants with a “summary of findings” (Appendix B). In actuality, the comments are not produced from analyzing the hundreds of interventions completed by students but from a brief overview of some of them. The intention of this component is not to accurately inform the students about the study but to make them reflect. Retrospectively thinking about the task performance, is meant to reinforce awareness of metacognitive skills and their transferability. Additionally, this feedback offers participants the opportunity to reflect about the activity as a learning experience stressing awareness and meaningfulness. This phase also builds a sense of group identity through the realization of peers sharing some of their own challenges, skills and opinions. It is here hypothesized that these combined factors may operate affectively to facilitate internalization of learning and skills, and improving motivation. Table 5.1 shows an overview of the design of the intervention.
Table 5.1: Collaborative Metacognitive Intervention Overview

<table>
<thead>
<tr>
<th>Phase</th>
<th>Focus</th>
<th>Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1</td>
<td>Collective reflection</td>
<td>Promote reflection about metacognitive skillfulness by use of prompts and social interaction. One non chemistry problem followed by 26 directed prompts. In-lab exercise (Week 1), approximate duration of 45 minutes, collaborative work, teams of 2 or 3 participants.</td>
</tr>
<tr>
<td>Phase 2</td>
<td>Individual reflection</td>
<td>Reinforce skills practiced during collaborative phase.</td>
</tr>
<tr>
<td>Phase 3</td>
<td>Feedback and summary of findings</td>
<td>Provide summary of findings compiled from students’ responses, reflecting of activity as learning experience.</td>
</tr>
</tbody>
</table>

The collaborative metacognitive intervention was pilot-tested with a small group of General Chemistry 1 students prior to its use in the study whose results are presented in this chapter. The main objectives of the pilot-test were to verify intelligibility, to calibrate time of administration, and to fine tune instructions. Additionally, the effect of the intervention on the self-report use of metacognition was pilot-tested using a control-treatment design. Thirty one students completed the MCA-I before and after the intervention while a group of 17 participants completed the self-report at the same times but without having had the experience of the intervention. Procedures for the administration of the MCA-I followed the protocol described in previous chapters. The
time lapsed between the two measurements was six weeks. Results for this pilot assessment are presented in sections ahead. Observation during pilot-testing also allowed determining that students did indeed spontaneously engage in team discussion. One tendency observed, which was certainly recurrent during the main study, was to spontaneously extend the discussion to neighboring teams. It is believed that this extended discussion was the result of intense engagement and was allowed during the main study but at the same time monitored to prevent distractions from the activity’s main goals.

Methodology

Data collection utilized the multimethod assessment (Metacognitive Activities Inventory, MCA-I; and IMMEX, Hazmat problem set) as described in Chapter Four. The experiment followed a control and treatment group design with both instruments of the multimethod used for the pretest and the posttest measurements. The purpose was to quantify changes in strategy and metacognition use and awareness that could be associated with the intervention. Participants were students enrolled in General Chemistry Laboratory. Sections were assigned to either condition so that: (1) there were about the same number of sections from all scheduling blocks in the two conditions; (2) there was at least one section from each TA in each condition (typically TAs teach three laboratory sections); (3) the initial number of students in the two conditions was similar. The intervention was part of the required assignments and was given credit based on satisfactory completion. Only data from participants who signed informed consent forms (Appendix C) was included in the study, and identification numbers were assigned to
assure confidentiality. To account for fairness in learning opportunities, students in the control condition completed the intervention towards the end of the semester and only after the posttest had taken place and study data gathering had been completed. Neither the laboratory instructor nor the TAs were part of the research team and even though they were aware of data collection, they were unaware of the scope and nature of the research questions. Researchers did not have any instructional contact with participants; nor did they supervise the graduate students serving as TAs. This was deemed necessary to prevent students’ performance being influenced by researchers’ expectations. TAs read to their students the scripted instructions for the completion of the intervention. During the administration, a research group member was available in the laboratory room to address questions and verify that students remained on task.

Pretesting using the MCA-I took place during the first week of laboratory instruction. The IMMEX assessment problem set, Hazmat, was assigned on the same day (Week 1) and students were given a full week to complete six cases. Both conditions worked on their regular experimental project (Weeks 1-4); during the beginning of the fifth week meeting, the treatment sections completed the collaborative component (Phase 1) of the Problem-Solving Exercise intervention. One week later (Week six) students in the treatment condition turned in the individual homework portion (Phase 2) and received the third component containing feedback (Phase 3). No alternative activities were assigned to the control condition during this period of time. All students had previously been informed that due to limitations associated with the large enrollment of the course not all sections would be performing the same tasks at the same time. Posttest of the
MCA-I was administered to all students, control and treatment conditions, during Week Six. This same day, the IMMEX posttest was assigned and again participants had one full week time to complete the assignment (due on or before Week 7). Figure 5.1 shows the experimental design used for the treatment condition. Phases 1, 2 and 3 refer to the three stages of the intervention. The control condition did the same activities except for these three intervention phases.

![Figure 5.1: Experimental Design Used for the Collaborative Intervention Condition](image)

The four parameters used to assess the effect of the collaborative metacognitive intervention are shown in Table 5.2.
Table 5.2: Parameters for the Collaborative Intervention Study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Representation</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strategy</td>
<td>Metacognitive characterization of solution of qualitative inorganic unknowns.</td>
<td>States: high, H; intermediate, I, and low, L.</td>
<td>Hazmat (IMMEX ANN and HMM modeling)</td>
</tr>
<tr>
<td>Ability</td>
<td>Maximum difficulty level of a case that a participant can probably solve</td>
<td>20-80 range, dimensionless</td>
<td>Hazmat (IMMEX performance IRT modeling)</td>
</tr>
<tr>
<td>Solve rate</td>
<td>Ratio of cases solved correctly over total number of cases.</td>
<td>% correct</td>
<td>Hazmat (IMMEX case correctness)</td>
</tr>
<tr>
<td>MCA%</td>
<td>Self-reported use of metacognitive regulatory skills.</td>
<td>% summative scale</td>
<td>Metacognitive Activities Inventory</td>
</tr>
</tbody>
</table>

Results

The pilot-test was exploratory in nature and, as explained above, it was mostly envisaged as a way to fine tune the design and development of the intervention. However, the preliminary results obtained for the assessment of the effect of the intervention on students’ self-report of use of metacognition proved to be significant for the discussion of the main study. Therefore these preliminary observations are presented in Table 5.3. This table shows that a decrease in MCA-I score occurred for both, control and treatment conditions, however, this decrease in MCA-I score was statistically significant only for the treatment group. It is also noteworthy that in both case, pre and posttest measures were significantly correlated.
Table 5.3: Pilot-Test Effect of Collaborative Metacognitive Intervention on Self-Reported Metacognition Use (Paired Sample t-Test)

<table>
<thead>
<tr>
<th>Group (n)</th>
<th>MCA-I%</th>
<th>p (Paired samples)</th>
<th>r (sig.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control (17)</td>
<td>Pretest: 76.9</td>
<td>Posttest: 76.3</td>
<td>.77</td>
</tr>
<tr>
<td>Treatment (28)</td>
<td>Pretest: 76.1</td>
<td>Posttest: 73.8</td>
<td>.045</td>
</tr>
</tbody>
</table>

For the main study, an association test for strategy distribution on the IMMEX problem Hazmat, (chi square association test) showed no significant difference between the control and the treatment groups. However, significant changes occurred for the self-reported use of metacognition, and Hazmat ability and solve rate. Table 5.4 shows the significant decrease in MCA-I score for the treatment group while this parameter did not vary significantly for the control group. In both case, pre and posttest measures were significantly correlated.

Table 5.4: Effect of Collaborative Metacognitive Intervention on Self-Reported Metacognition Use (Paired Sample t-Test)

<table>
<thead>
<tr>
<th>Group (n)</th>
<th>MCA-I%</th>
<th>p (Paired samples)</th>
<th>r (sig.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control (537)</td>
<td>Pretest: 76.0</td>
<td>Posttest: 75.3</td>
<td>.07</td>
</tr>
<tr>
<td>Treatment (464)</td>
<td>Pretest: 76.3</td>
<td>Posttest: 74.6</td>
<td>&lt; .000</td>
</tr>
</tbody>
</table>
Table 5.5 shows the pre and posttest results for Hazmat ability. A statistically significant change in the ability of the treatment group was observed meaning that students could solve problems of higher difficulty level. The same table shows that the correlation between ability measures for the first and the second Hazmat assignments was significant for both conditions.

**Table 5.5: Effect of Collaborative Metacognitive Intervention on Ability. (Paired Sample t-Test)**

<table>
<thead>
<tr>
<th>Group (n)</th>
<th>Ability</th>
<th>p (Paired samples)</th>
<th>r (sig.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pretest</td>
<td>Posttest</td>
<td></td>
</tr>
<tr>
<td>Control (188)</td>
<td>51.2</td>
<td>51.8</td>
<td>.45</td>
</tr>
<tr>
<td>Treatment (159)</td>
<td>50.7</td>
<td>53.6</td>
<td>.003</td>
</tr>
</tbody>
</table>

A chi square association test of the correct solutions for the first and second Hazmat assignment shows that only the treatment group increased its solve rate significantly (Table 5.6).
Table 5.6: Effect of Collaborative Metacognitive Intervention on Solve Rate. (Paired Sample t-Test)

<table>
<thead>
<tr>
<th>Group (performances)</th>
<th>% Correct</th>
<th>$\chi^2$ (p-Value)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pretest</td>
<td>Posttest</td>
</tr>
<tr>
<td>Control (1124)</td>
<td>62.2</td>
<td>62.5</td>
</tr>
<tr>
<td>Treatment (956)</td>
<td>60.4</td>
<td>66.3</td>
</tr>
</tbody>
</table>

Discussion

This research contributes to the understanding of the effect of metacognitive instruction on metacognitive awareness and use. Preliminary assessment of the effect of the intervention on self-report use of metacognition indicated that the MCA-I score decreased significantly for the treatment condition. Since the sample size for this exploratory study was small (Table 5.3) findings were considered cautiously. However, the same trend was observed for the main study with a much larger sample size: Participants who were administered the intervention scored significantly lower in the MCA-I posttest while there was no significant change for the control group (Table 5.4). The statistical test employed (the paired sample t-test) scrutinizes the significance of the change in the measurement for a given condition and does not run comparisons between conditions. That is, it looks at a given condition at two different times. Initially, this decrease in the treatment group may seem contradictory since one would tend to believe that by becoming more aware of metacognition, individuals would increase their self-report of its use. However, attention must be drawn to the fact that the MCA-I is a
habitual behavior self-report and not an attitude inventory. In other words, it is not the importance that participants place on the construct that is assessed but their habitual use of it. So in fact, by raising the awareness about metacognition and increasing its perceived importance, participants develop a more critical self-view and tend to self-rank more strictly, thereby lowering their scores. This behavior upon raising awareness is commonly described as consequence of a shift in the point of reference used when self-reporting (Thorndike, 2005).

No significant change in strategy use was detected for either condition. Initially, it was hypothesized that if the metacognitive intervention succeeded in enhancing participants’ use of metacognition, this would be reflected in the distribution of strategy states during the IMMEX posttest. An increase in the percentage of the treatment group students using more efficient strategies, particularly State 5, was expected. However, even though the treatment condition presented a slight percent increase in Strategy 5, it was not significant.

An explanation for this observation was in fact obtained from the study described in the following chapter: the effect of the laboratory project on use and awareness of metacognition. As will be seen in Chapter Six, the cooperative problem-based project used as first experimental assignment has a significant effect on the students’ development of Hazmat strategies. Since for the study presented in this chapter, participants in both conditions completed the laboratory experiment between the pretest and the posttest (Figure 5.1), it is reasonable to believe that the lab’s effect might have masked the effect of the intervention. This argument does not assume that there was an
effect of the intervention on the strategy; it only suggests the plausibility of such an effect to go undetected. The experiment to remove the effect of the laboratory is not practical under present circumstances since students cannot be deprived of the lab learning experience!

After participating in the collaborative metacognitive intervention, students have a significantly increased ability to solve Hazmat problems (Table 5.5). This implies that they can solve problems of higher difficulty; this was not observed for the control condition whose ability remained statistically unchanged. Solve rate results (Table 5.6) also support this observation: only the treatment condition students significantly increased their percentage of correct solutions. Given that metacognition use has been described as a determinant factor in success solving ill-structured problems like Hazmat, it can be suggested that these results indicate that the intervention has indeed enhanced the use of metacognitive skills. This actual increase in deployment of metacognitive skills is in agreement with the increase in metacognitive awareness evidenced by the drop in MCA-I scores discussed above. This finding, the convergence of the two instruments in detecting a change meant to be induced by an intervention, further advances the construct validity evidence presented in Chapter Four for the multimethod assessment.

The fundamental question that arises is: What are the processes that underlie this effect? How is the collaborative metacognitive intervention enhancing awareness of metacognition and enabling students to perform more metacognitively? Literature review and critical analysis of the results suggest an interpretation that combines two contributing factors: prompting and collaborative interaction. According to Kaufman
(KAUFFMAN, 2004), research on how to prompt students to use their existing metacognitive skills is rare and has focused more on describing existing processes and their relationship with specific learning environments. Kaufman studied how metacognitive prompts influenced students’ ability to solve ill-structured web based problems. He described two different kinds of prompts: problem-solving prompts, which are procedural questions to guide the participant’s problem-solving process; and reflection prompts, which simply encourage participants to reflect on their problem-solving process and outcome. An example of the former is “What do you see as the primary problem?”; an example of the latter is “How certain are you that you have identified the primary problem”. Kaufman found that problem-solving prompts helped students improve problem-solving (quality of solution) and the clarity, fluency and argumentation of their writing (writing was used as the way to communicate the solution). Evidence in the case of students who were only prompted to reflect was not conclusive.¹

Somewhat opposing evidence was reported by Davis (Davis, 2003; Kauffman et al., 2008) who distinguished between generic prompts (the type that just asks students to stop and think as means of inducing reflection) and directed prompts (in which students are given hints to direct their reflections in a specific way). Among her findings, Davis cited middle school students in the generic condition gaining a more coherent understanding of a complex science project. Those students in the directed prompt

¹ Participants were college education majors enrolled in an educational psychology course. The problem task dealt with two classroom management scenarios for which students had to provide written analysis and recommendations to a fictitious teacher.
condition reflected more unproductively and were less successful in their task performance. Settlement of this apparent controversy is not a goal of this work but it is relevant to point out that there are multiple factors that shape the outcome of using prompts. Careful interpretation must precede generalization of findings. One aspect on which there is widespread acceptance is that adequate prompting promotes reflection and thereby use of metacognitive skills (Davis, 2003; Kauffman et al., 2008). Some of the characteristics of prompting that should be considered are: the nature and intention of prompts, the thoughtfulness in the design of prompts, the methods of delivery, the characteristics of the participants (for instance, autonomous learners respond different from dependent learners to the same type of prompt).

Prompting in this study—the first contributing factor in interpreting how the metacognition enhancement occurred—is characterized by two main aspects. The first one deals with the nature of prompting: The object of reflection is reflection itself, students are prompted to reflect about their use of metacognitive skills. The goal of the prompts is not to help students complete a task. That is: the students’ goal is not to correctly solve the problem presented in the intervention but to learn problem-solving skills from the exercise. This is what Davis (Davis, 2003) called explicitly metacognitive prompts, the emphasis is placed on the process and not the product of this particular problem-solving instance. The effect of prompts cueing students to self monitor and consequently to be more self regulating has been reported (Davis, 2003; Kauffman et al., 2008). This is in line with the observations discussed above that indicated an increased awareness about metacognition by a drop in the MCA-I score.
The second aspect regards the timing of the prompts. Typically, in studies like Kaufman’s (Kauffman et al., 2008) prompts are delivered while students work on the assessment task. In the present study prompting and task assessment were not simultaneous which carries a significant meaning since this study actually looks at the transfer of the elicited skills. Success of the intervention was not measured by performance on the immediate task given (intervention problem) but by performance on a task which for students’ practical purposes was unrelated (the IMMEX Hazmat problem set). Furthermore, the task was removed from the physical environment where the intervention took place since students completed their online assignments away from the laboratory. The results suggest that transfer of general metacognitive skills is possible at least over a short period of time. (The assessment task was assigned the same day of the intervention and to be completed within a week.). Enhanced achievement while prompting students during task performance (with automated computer generated support or instructor’s support) does not evidence students’ ability to independently use the evoked skills. As described in the introduction to this dissertation, the overarching goal of this research is to investigate ways in which students can enhance their autonomous learning and move closer to be independent thinkers. The results presented in this chapter suggest that this goal is achievable through the use of learning environments such as the intervention used here. This finding becomes even more important if one considers that habitual practice of metacognitive skills can lead to internalization and automation of those skills.
The second factor contributing to explaining the effectiveness of the intervention is its collaborative nature. Even though the prompts were formatted, delivered and responded in writing, reflection was not only evoked by the prompts themselves but also potentiated and magnified by the interaction with other students. Phases 2 and 3 were performed individually but were of a shorter duration and as indicated before they served the purpose of individually consolidating the skills practiced within the collaborative team. There is a large body of literature supporting the benefits of collaborative learning and task performance. Previous reports regarding the effect of interventions (E. Case et al., 2007; Cooper et al., 2008) found that students participating in small group collaborative work increased their IMMEX problem-solving strategy and significantly outperformed peers whose only experience with the problems had been individualistic. Similarly, Cooper (Cooper et al., 2007) described gains in strategy and performance in solving of the online problems for participants of a small collaborative group condition that had been instructed in the creation and use of concept maps. In another collaborative approach, Think Aloud Together, or TAT, engaged students in peer prompting and was designed by Hogan (Hogan, 1999) to foster students’ collaborative scientific reasoning. Results from a study with eighth graders indicated that students who were asked to self-explain while reading a science passage achieved higher understanding than those who were not prompted (Chi, De Leeuw, Chiu, & Lavancher, 1994). That study is in agreement with previous findings indicating the effectiveness of self-explaining as a learning strategy (Chi, Bassok, Lewis, Reimann, & Glaser, 1989). Collaborative work promotes reciprocal explaining which can be thought of as an extension of self-
explaining. Hausmann and collaborators (Hausmann et al., 2004) have gathered evidence that supports three mechanisms to describe why collaboration is effective in enhancing understanding and task performance. *Other-directed explaining*, the first mechanism, describes how a member of the team takes the stance of a teacher or instructor. Since the interaction is open and flexible in the collaborative metacognitive intervention, both members have the opportunity to engage in other-directed explaining. The second mechanism is called co-construction, most frequently expressed as elaboration or critical evaluation of peer’s contributions. It occurs when a member responds to or picks up someone else’s ideas and extends and/or critiques them. In the third mechanism, *self-directed explaining*, individuals learn, gain understanding, or enhance their awareness from simply listening to others’ self-explaining. These mechanisms are not mutually excluding, and in fact the intervention used in this study makes it possible for the three of them to take place alternatively during Phase 1. As annotated before, engagement in argumentation and discussion was observed to extent among teams. The descriptions of the three mechanisms proposed by Hausmann and collaborators and their evidence (Hausmann et al., 2004) support the practice of metacognitive skills during collaboration. Reflection is necessary in the three mechanisms to explain, elaborate or critically evaluate one’s own or others’ ideas. Monitoring and evaluating are being practiced as students reflect about metacognition use.

It is therefore reasonable to speculate based on reported studies and the findings presented here, that the combination of prompting and collaborative work creates a
learning environment effective in conducting to the practice and enhancement of metacognitive skills.

Conclusion

The primary goal of the present study was to investigate the effect of the collaborative metacognitive intervention on metacognition use and awareness as gauged by using the multimethod assessment described in previous chapters. The effectiveness of the intervention in enhancing metacognition use and awareness was successfully documented. The processes that underlie this enhancement are attributable to the combined effects of prompting and small group collaboration. This work makes two major contributions. First it utilized a multimethod for the assessment of the impact of an intervention on metacognition use and awareness; literature review suggests that this has not been done before in the field of tertiary science education. Second, it presents evidence to claim that metacognitive skills developed during collaboration are transferable to the individual solution of an unrelated and independent task.

Implications for teaching

Throughout this work, the positive influence of regulatory skills in learning and problem-solving has been repeatedly underscored. Findings from this study support the usefulness of an intervention that combines collaboration and direct prompting in developing general awareness and use of regulatory metacognition. Larkin proposed that “Asking questions of oneself can begin by being questioned by others” (Larkin, 2006); here strategies that actually succeed in making students stop and think, and in questioning them through prompting and collaboration helped them become more reflective and
aware of their own problem-solving. Chemistry teachers can take advantage of the simplicity in implementation of these factors—prompting and collaboration—and imbed short activities during instruction. Additionally, the intervention presented in this chapter can be modified or used as is to integrate a problem-solving activity to the course curriculum.
CHAPTER SIX

EFFECT OF COOPERATIVE PROBLEM-BASED LAB PROJECTS ON METACOGNITION USE AND PROBLEM SKILLS AND PERFORMANCE

Introduction

Even though some argue that research shows that laboratory work often “achieves little meaningful learning by students” (Hart, Mulhall, Berry, Loughran, & Gunstone, 2000), most chemistry educators agree upon its relevant place in the curriculum (Cooper & Kerns, 2006; Wojcik, 1990). Unfortunately, another aspect on which consensus seems to have been reached is that the traditionally structured laboratory is not accomplishing pedagogical objectives significant for science literacy (Gabel, 1999; Mohrig, 1994), such as, problem-solving skills, critical thinking, and experiment design and implementation (Domin, 2007; Kirschner & Meester, M. A. M., 1988; Lagowski, 1990). Paradoxically, traditional laboratory instruction prevails as the choice in most chemistry departments (Hilosky, Sutman, & Schmuckler, 1998) (McDonnell, O’Connor, & Seery, 2007) providing evidence that chemistry education research “has had little influence on the way chemistry is taught” (Gabel, 1999).

The realization of this discrepancy has resulted in researchers developing and implementing an array of novel instructional techniques commonly clustered under terms like “non traditional” or “non-conventional”, thereby clearly differentiating them from traditional methods (Abraham & Pavelich, 2004; Birk, Bauer, & Sawyer, 2001; Mattox, Reisner, & Rickey, 2006; Tien et al., 2007). Certainly, this dichotomous classification oversimplifies the situation by overlooking significant differences among the “non
traditional” techniques. Domin (Domin, 2007) has proposed an alternative classification based on three descriptors: approach taken (deductive or inductive), whether the outcome is known or unknown to the student, and source of the procedure (given or student generated). This taxonomy generates fours styles: expository (traditional), inquiry, discovery, and problem-based. Whether one agrees with Domin’s classification or not, what seems to be of outermost interest to research in laboratory instruction is realizing the need for deeper understanding of the singularities of different styles and the extent they may be complementary.

Even though supported by strong theoretical (Bodner, 1986) and anecdotal considerations, in most cases alternatives to the verification or traditional laboratory paradigm lack solid evidence for their efficacy. A decade ago, Hilosky (Hilosky et al., 1998) pointed out that many curriculum developments made no clear reference to results of research on how laboratory based instruction occurred or to the role laboratory experiences played in chemistry instruction. Among the few notable exceptions that are supported by research, Hilosky mentioned the General Chemistry Program in place at Clemson University (Cooper, 1994; Cooper, 2005) where cooperative problem-based laboratory projects successfully substituted traditional verification experiences more than a decade ago (Cooper & Kerns, 2006)

In general, findings indicate that metacognitive strategy instruction facilitates learning and problem-solving (Lin, Schwartz, & Hatano, 2005). It has been suggested that an environment conducive to social interaction and reflection could possible lead to meaningful learning in the laboratory (Hofstein & Mamlok-Naaman, 2007). For Hofstein
(Hofstein & Mamlok-Naaman, 2007) this can be equated with creating more opportunities for students to develop and use metacognitive skills during lab instruction which in turn can enhance understanding. According to Bodner (Bodner, 1986) such opportunities to learn actively improve retention and develop deeper understanding. In other words, a laboratory environment that promotes the use of metacognition helps students construct knowledge by doing science, by engaging them in “minds-on as well as hands-on” experiences (Bodner, 1986; Hofstein & Lunetta, 2004).

As discussed in Chapter Two, systematic observations of students working in the MORE learning environment have evidenced the eliciting of metacognitive skills (D. Rickey, 1999). However, no specific evidence has been collected that directly probes the role of metacognition in chemistry laboratory instruction. Previous reports regarding the effect of interventions (E. Case et al., 2007; Cooper et al., 2008) found that students increased their problem-solving strategy after participating in collaborative work. In a pre/post-test experiment, participants who had previously solved online ill-structured problems in a small collaborative group outperformed students in an individualistic-only experience control condition. Similarly, Cooper (Cooper et al., 2007) described gains in strategy and performance in solving of the online problems for participants of a small collaborative group condition that had been instructed in the creation and use of concept maps. In both cases, the exercise of metacognition during the intervention was suggested as a cause for the observed improvements. However, lack of an adequate measurement tool prevented the assessment of metacognition use in these studies. Enhancement of metacognition by the activities utilized in these learning experiences remained a plausible
explanation for the findings encountered. Chapter Five has described a study that supports this hypothesis by assessing the increase in metacognition use and awareness caused by a short term collaborative metacognitive intervention. The goal of the study presented in Chapter Six is to further investigate that hypothesis. This time the focus is not on using a well structured, short term group activity but on the open-ended laboratory learning environment. This work probes the effectiveness of laboratory cooperative problem-based project instruction in developing problem-solving skills and performance as assessed by using IMMEX (as described in Chapter Four). Additionally, changes in the self-report use of metacognition related to the laboratory instruction are measured by means of the Metacognitive Activities Inventory (MCA-I) as described in previous chapters (Chapters Three and Four). Potential benefits from this study can be viewed from two different perspectives. First, it collects evidence of the plausible enhancement of metacognitive skillfulness in purposefully designed learning environments. Second, this study aims at contributing to fill the void of research showing “simple relationships between experiences in the laboratory and student learning” that has been described in previous reviews (Hofstein & Mamlok-Naaman, 2007). The laboratory project chosen for this study is described in the following section.
Description of the Laboratory Cooperative Project

The project chosen for this investigation is entitled “Identification, Properties and Synthesis of an Unknown Ionic Compound” (Cooper, 2009). It is the first one in a two-semester General Chemistry laboratory sequence fully converted to the cooperative format over a decade ago (Cooper, 1994; Cooper, 2005). According to the instructor’s manual (Cooper, 2006):

The laboratory course described in the lab manual emphasizes experimental design, data analysis, and problem-solving. Inherent in the design is the emphasis on communication skills, both written and oral. Students work in groups on open-ended projects in which they are given an initial scenario and then asked to investigate a problem. There are no formalized instructions and students must plan and carry out their own investigations. (p. 3)

In addition to a teaching assistant training program developed at the beginning of the year, weekly meetings held by the laboratory coordinator are used to support adequate adherence to the guidelines of cooperative work project based instruction. Teaching assistants introduced students to the instruction style during the first meeting of the laboratory class. During this first meeting, students were randomly assigned to work in teams of four and remained together for the extent of the term; each participant had specific functions within the team that could be rotated after completion of each project. Typically four to six projects are conducted during one semester, and each lab section accommodates between four and six teams.
For the project under study, teams are presented with a scenario that intends to create a meaningful context. The goals are explicitly stated in the laboratory manual (Cooper, 2009), namely:

1. Identify the unknown compound.
2. Discover as many chemical and physical properties of the compound as you can.
3. Devise two syntheses of the compound, and compare them for cost effectiveness, safety and potential yield of compound. (p. 115)

Since the problem is explicitly provided to the students this project falls under inquiry Level 2 in Fay et al. (Fay, Grove, Towns, & Bretz, 2007) rubric scaled from 0 to 3. In Domin’s taxonomy, this laboratory experience would be described as “problem-based style” with the outcome known to the students who have to generate the procedure. However, Domin maintains that inductive approach is unique to his inquiry and discovery styles making problem-based lab experiences necessarily deductive. The case in question here would be better described as inductive: Students are not exposed to the general principles before the lab and the generalizations they may arrive at stem from their data collection and observations. The project spans over a period of four weeks of minds-on and hands-on work time during which the team analyzes the problem, sets intermediate goals, plans strategies, designs and implements experiments, learns necessary lab techniques, discusses and evaluates processes and outcomes, answers guiding and planning questions and so forth. During the laboratory periods, TAs are available to guide students, help them with techniques and equipment, and support them
in their experimental process. However, TAs are not a source of straight answers or procedural instructions; they act as facilitators in the process of inquiry. The four-week practical component of the project is followed by a session of group oral presentations for which the use of a poster as visual support is required. Teams communicate their procedures and rationales behind their decisions and conclusions, and their findings, and they respond to questions from the TA and peers. The improbability of two projects being closely similar encourages students to engage in knowledgeable discussion during presentations. Participants submit individual written preliminary reports that are corrected once by the TA before the final reports are due. In sum, the project not only facilitates but makes indispensable the exercise of an array of varied regulatory metacognitive skills that fall in the fundamental categories of planning, monitoring and evaluating. In addition, it relies on constant and intense social interaction to encourage and reinforce these metacognitive processes. A copy of the laboratory project can be found in Appendix D.

**Methodology**

Quantitative data collection utilized the multimethod assessment (Metacognitive Activities Inventory, MCA-I; and IMMEX, Hazmat problem set) as described in Chapter Four. The purpose was to quantify changes in strategy and metacognition use and awareness that could be associated with the intervention. It is important to emphasize that this study is not comparative in nature; its intention is not to examine the use of two different instructional approaches but to collect evidence on the effectiveness of the one chosen as treatment.
Participants were students enrolled in General Chemistry 1 Laboratory, the first of a two-course sequence in a program that is fully cooperative work project based. Therefore, the study did not impose any additional work on the students who were simply completing the task as part of their course assignments. Only data from participants who signed informed consent forms was included in the study, and identification numbers were assigned to assure confidentiality. Neither the laboratory instructor nor the TAs were part of the research team and even though they were aware of the data collection, they were unaware of the scope and nature of the research questions. Researchers did not have any instructional contact with the participants; neither did they supervise the graduate students serving as TAs. This was deemed necessary to prevent students’ performance to be influenced by researchers’ expectations.

The multimethod assessment of metacognition was done as explained in Chapter Four; the IMMEX problem set employed was Hazmat. The investigation of the effect of the cooperative laboratory project on regulatory metacognition use, problem-solving strategy and performance was conducted by duplicate (main and replication studies). The effect on self-report of metacognition use was done once. All students were members of teams of four (three in rare cases). Data collection was conducted over a period of four semesters and completed using condition groups as described in Table 6.1.
Table 6.1: Description of Condition Groups Used During the Four-Semester Study

<table>
<thead>
<tr>
<th>Semester</th>
<th>n</th>
<th>Group identifier</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>234</td>
<td>NoLab1</td>
<td>IMMEX assignment completed before any laboratory work</td>
</tr>
<tr>
<td>2</td>
<td>410</td>
<td>PostLab1</td>
<td>IMMEX assignment performed after completion of laboratory project</td>
</tr>
<tr>
<td>3</td>
<td>145</td>
<td>NoLab2</td>
<td>Replication of NoLab1: IMMEX assignment completed before any laboratory work</td>
</tr>
<tr>
<td></td>
<td>114</td>
<td>PostLab2</td>
<td>Replication of PostLab1: IMMEX assignment performed after completion of laboratory project</td>
</tr>
<tr>
<td>4</td>
<td>509</td>
<td>PostLab3</td>
<td>Pretested first week of lab using MCA-I, completion of the cooperative work lab project, and then post-tested using MCA-I.</td>
</tr>
</tbody>
</table>

All pretesting, IMMEX and MCA-I, was done the first week laboratory sections met. Post-testing was done immediately after the fifth week of laboratory instruction, once all activities related to the project had been finished. Table 6.2 summarizes the study design employed. Comparison groups NoLab1 and PostLab1 (sequential semesters) comprise the main study; the replication study consisted of comparison groups NoLab2 and PostLab2 (concurrent groups) (Table 6.2). These two control and treatment group studies addressed the effect of the cooperative work lab project on problem-solving strategy and performance assessed by using IMMEX. Homogeneity in both studies was evaluated by comparing the strategy distribution for the first case; there was no significant difference between the PostLab and the NoLab groups. Use of sequential semesters in one case and concurrent in the other responded to convenience in the process.
of data collection. **PostLab3** corresponds to the one-group pretest-posttest design study (Ravid, 2005) to assess the effect of the lab project work on the self-reported use of metacognition as measured by the MCA-I.

### Table 6.2: Experimental Design Used for the Lab Cooperative Project Study

<table>
<thead>
<tr>
<th>Semester</th>
<th>Condition</th>
<th>Pretest</th>
<th>Treatment</th>
<th>Posttest</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NoLab1 (control)</td>
<td>IMMEX (Hazmat)</td>
<td>Lab project</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>PostLab1 (treatment)</td>
<td>---</td>
<td>Lab project</td>
<td>IMMEX (Hazmat)</td>
</tr>
<tr>
<td>3</td>
<td>NoLab2 (control)</td>
<td>IMMEX (Hazmat)</td>
<td>Lab project</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>PostLab2 (treatment)</td>
<td>---</td>
<td>Lab project</td>
<td>IMMEX (Hazmat)</td>
</tr>
<tr>
<td>4</td>
<td>PostLab3</td>
<td>Pre-MCA-I</td>
<td>Lab project</td>
<td>Post-MCA-I</td>
</tr>
</tbody>
</table>

Participants were instructed to solve six cases of the IMMEX Hazmat problem set and were given a full week to complete the online assignment. Only students who completed five or more cases were included in the analysis to ensure strategy stabilization. Hazmat data were modeled by the IMMEX Project as described previously (Chapter Four), thereby obtaining state and ability reports for each participant. The state strategy and ability correspond to those attained by participants once they had stabilized (6th case).

For the administration of the Metacognitive Activities Inventory, MCA-I, hard copies were used and responses were entered on optical reader answer sheets. Typically, completion of the instrument took about 15 minutes and was done at the beginning of the
lab under the supervision of the TA and a researcher. Incomplete inventories and those in which a verification item was wrong were discarded. Additionally, only students who satisfactorily completed both administration of the instrument were considered for the study (80% of the original sample, the remaining 20% corresponded to participants who were absent or presented any of the following during either administration of the instrument: damaged scantrons, blank items, multiple responses to a single item, missing identification information, failed verification item). SPSS 15.0 was employed for means comparisons (analyses of variance and t-tests), as well as association tests (chi square) and other descriptive statistics.

Table 6.3 summarizes the four parameters used to assess the effectiveness of the lab cooperative project.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Representation</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strategy</td>
<td>Metacognitive characterization of solution of qualitative inorganic unknowns.</td>
<td>States: high, H; intermediate, I, and low, L.</td>
<td>Hazmat (IMMEX ANN and HMM modeling)</td>
</tr>
<tr>
<td>Ability</td>
<td>Maximum difficulty level of a case that a participant can probably solve</td>
<td>20-80 Range, dimensionless</td>
<td>Hazmat (IMMEX performance IRT modeling)</td>
</tr>
<tr>
<td>Solve rate</td>
<td>Ratio of cases solved correctly over total number of cases.</td>
<td>% Correct</td>
<td>Hazmat (IMMEX case correctness)</td>
</tr>
<tr>
<td>MCA%</td>
<td>Self-reported use of metacognitive regulatory skills.</td>
<td>% Summative scale</td>
<td>Metacognitive Activities Inventory</td>
</tr>
</tbody>
</table>
Results

Figure 6.1 shows the effect of completing the lab project on strategy. The percentage of participants in the treatment group (PostLab1) that used strategies of the highest metacognitive characteristics more than doubled the corresponding percentage for the control NoLab1 group. The difference in distribution is significant as indicated by the chi square test ($\chi^2 = 15.5$, $p < .000$).

![Figure 6.1: Effect of the Lab Project on Hazmat Strategy Distribution](image)

Table 6.4 shows the results for the t-test ability mean comparison between the PostLab1 and NoLab1 groups. The difference between the groups is statistically significant. Frequency distribution comparison for correctness of solution using a chi square test is consistent with the results above: Solve rate for the PostLab1 group is significantly higher, Table 6.5.
Table 6.4: Effect of the Lab Project on Ability ($F = 21.5$, $p < .000$)

<table>
<thead>
<tr>
<th>Group (n)</th>
<th>Mean ability</th>
</tr>
</thead>
<tbody>
<tr>
<td>PostLab1 (410)</td>
<td>48.9</td>
</tr>
<tr>
<td>NoLab1 (234)</td>
<td>44.6</td>
</tr>
</tbody>
</table>

Table 6.5: Effect of the Lab Project on Solve Rate ($\chi^2 = 45.0$, $p < .000$)

<table>
<thead>
<tr>
<th>Group (n)</th>
<th>% Correct</th>
</tr>
</thead>
<tbody>
<tr>
<td>PostLab1 (410)</td>
<td>41.4</td>
</tr>
<tr>
<td>NoLab1 (234)</td>
<td>31.0</td>
</tr>
</tbody>
</table>

Table 6.6 summarizes the results corresponding to the replication study. The trend observed was similar to that for the main study with the only difference occurring in the case of the significance of the difference for the ability. In the replication study, the advantage of the PostLab2 group over the NoLab2 group is less significant than in the main study.

Table 6.6 Summary for the Comparison of PostLab2 and NoLab2 Groups, Replication Study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>State distribution</td>
<td>.005</td>
</tr>
<tr>
<td>Ability</td>
<td>.07</td>
</tr>
<tr>
<td>Solve rate</td>
<td>.006</td>
</tr>
</tbody>
</table>
No significant gender differences were observed for the three parameters reported above: strategy, ability and solve rate.

Results for the effect of the lab project on self-reported use of metacognitive skills are shown in Table 6.7. The paired sample t-test shows there was a significant decrease in the MCA-% value for the PostLab3 condition. Investigation of the magnitude of the effect by gender showed that the decrease was significant in the case of male participants but not so in the case of females. Correlations of pre post-test results evidence the robustness of the instrument.

Table 6.7: Effect of the Lab Cooperative Project on Self-Reported Metacognition Use

<table>
<thead>
<tr>
<th>Group (n)</th>
<th>MCA% Before lab project</th>
<th>MCA% After lab project</th>
<th>Correlation r (p)</th>
<th>Paired sample t-test t (p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Females (219)</td>
<td>77.60</td>
<td>76.51</td>
<td>.46 (&lt; .000)</td>
<td>1.52 (.13)</td>
</tr>
<tr>
<td>Males (290)</td>
<td>75.86</td>
<td>74.51</td>
<td>.44 (&lt; .000)</td>
<td>2.11 (.04)</td>
</tr>
<tr>
<td>PostLab3 (509)</td>
<td>76.61</td>
<td>75.37</td>
<td>.45 (&lt; .000)</td>
<td>2.59 (.01)</td>
</tr>
</tbody>
</table>

Discussion

The results presented here contribute evidence to gain understanding about the effect of cooperative problem-based laboratory instruction on metacognition use and awareness. As explained in the preceding sections, the most efficient strategy solving Hazmat is also characterized as the one that implies the most metacognition use. The gain in use of this strategy by the treatment condition (Figure 6.1) can be clearly interpreted as
evidence of this group performing more metacognitively as result of the laboratory work. This finding is consistent with the effect observed on self-reported use of metacognition (Table 6.7). The significant decrease in MCA-I score for the treatment group is caused by an increase in metacognitive awareness. (This effect is explained by a shift in the reference point of the participants as discussed in Chapter Five). The significance of these results is twofold: First, it constitutes evidence of the laboratory experience operating positively on students’ awareness and use of metacognition; second, it contributes more construct evidence supporting the use of the multimethod since both assessments detect the same direction in trend or behavior change. It is relevant to stress here that this concordance between the enhancement of actual deployment of metacognitive skills (Hazmat evidence) and increased awareness of metacognition use (MCA-I evidence) mirrors the findings obtained for the collaborative metacognitive intervention described in Chapter Five. Even though both males and females experienced a decrease in MCA-I score this effect was not significant for females (Table 6.7). At first, this may seem to contrast with reports that females tend to benefit more from interventions than males. However, the MCA-I is not a direct measure of the outcome but reflects the change in perception. It could be thought that females may have a more accurate or realistic self-report reference point and therefore less malleable by activities.

Tables 6.4 and 6.5 show higher ability and solve rate for the treatment group when compared to the control group. This effect of the lab project is in complete agreement with the enhancement observed for strategy and metacognition awareness and use. Whereas the effect on problem-solving strategy and self-reported metacognition use
addresses the feasibility of developing important scientific skills through laboratory instruction, the effect on ability and solve rate are evidence of learning in a more traditional sense. Students participating of the lab project are learning and achieving mastery of the materials without need of direct instruction and without relying on a transmission-only instructional model, this in itself is a valuable finding. As stated in the discussion for Chapter Five, metacognition use has been described as a factor in success solving ill-structured problems like Hazmat, therefore the increased ability and solve rate associated with participating in the treatment condition also serves as evidence of enhanced use of metacognitive skills.

There are many overlapping aspects in the discussion of the work presented in this chapter and the discussion in Chapter Five. This is not surprising at all since as stated above, the current chapter expands the investigation around the same hypothesis. Furthermore, results between the two studies are remarkably consistent. As discussed in Chapter Five, three approaches for teaching metacognition have been more frequently employed and have focused more on monitoring skills: strategy training (or direct instruction), creation of social environments to support reflective discourse, and modeling and prompting (Lin & Lehman, 1999; Lin et al., 2005). In addition to the intervention in Chapter Five, the laboratory cooperative problem-based project combines the latter two approaches but at the same time it is very distinct in its contextual characteristics from the collaborative metacognitive intervention and other interventions. The metacognition enhancement approach utilized in this study is novel in the sense that it is fully blended with instruction. As pointed out by Georghiades (Georghiades, 2006) often researchers
studying metacognition in science education have taught it as “a context-free general thinking skill, taking specially allocated time for this purpose”. Even though student teams are presented with an overall project objective, there is a myriad of smaller problems and challenges that have to be uncovered, defined and solved by the students as they advance. Unlike the intervention used in Chapter Five, there is no single well-defined problem. Challenges emerge naturally from the experimental practice, and evidently there is no single, optimal solution for the entire collection of problems. The learning environment is therefore open-ended and not stable in itself. Moreover, there is no single laboratory experience shared by all participants, not even by all members of a given team. Failure is a reasonable occurrence, especially for peripheral or intermediate tasks (for example, synthesizing of the unknown material or choosing of appropriate filtration procedures), and it is not rare for teams to be faced with the decision of aborting plans. Neither is there emphasis on a single component of regulatory metacognition, thereby increasing the chances of all students practicing the skills in which they are less competent. Commonly, the project requires teams to meet outside the laboratory period or interact via email extending practice beyond the confines of the laboratory room. Teams are assembled randomly creating an opportunity for negotiation regarding beliefs, values and goals. Metacognitive instruction is well blended in the curriculum to the point that students are not overtly trained in metacognitive skills. It is here hypothesized that these particular contextual characteristics enhance the development of metacognitive skills use and their transfer to diverse situations; furthermore, these skills are co-constructed and internalized inadvertently.
As a whole, the findings presented here reinforce this hypothesis. Hausmann and collaborators’ (Hausmann et al., 2004) mechanisms for the description of how collaborative interactions, or cooperative in this case, increase understanding and task performance are all operative in the laboratory intervention. Other-directed explaining, co-construction and self-directed explaining (Hausmann et al., 2004) are made necessary by the characteristics of the problem-based project. Investigations by other researchers on the effects of social interaction on learning support this explanation. Okita, Bailenson, and Schwartz (Okita et al., 2007) recently reported that the mere belief one is interacting with another person led to superior learning and postulated that it is the participation in socially relevant actions that promotes this favorable effect. The cooperative problem-based project does not only promote social interaction (as does the collaborative metacognitive intervention) but also emphasizes the participation in group actions that are relevant for the accomplishment of common goals. It is fair to think that completion of the laboratory project bears more relevance for the students than completion of a short term intervention. Two reasons may be suggested for this claim: First, students’ concern for their grades, much more affected by the project than by the short term intervention; second, the effect of situated learning, students learn and use their problem-solving skills in a more naturalistic problem-solving environment while completing the laboratory project. Based on the evidence collected, it is reasonable to assert that by emphasizing the utilization of social interaction, cooperative problem-based project work supports the effective development of metacognition through the exercising of skills such as reflective discussion, verbalization, think aloud, group planning, monitoring and evaluating.
Individually, students have the opportunity for these skills to consolidate through the preparation of written reports. Additionally, as mentioned above since the tasks are not rigidly structured, and no specific skills are targeted, individuals have the possibility to practice and strengthen those skills that are more necessary for them.

**Conclusion**

This study explored the outcomes of students being immersed in an environment that implicitly required the use of metacognitive skills. The findings from this study strongly support that laboratory cooperative problem-based projects assist in developing students’ problem-solving skills and metacognition use and awareness. The trend observed in terms of self-report of metacognition use (MCA-I), and problem-solving skills and performance (IMMEX strategy, ability and solve rate) parallels the results obtained with the use of the collaborative metacognitive intervention (Chapter Five).

A significant accomplishment of this study is that it reveals evidence that indicates that meaningful learning can occur through laboratory instruction. This learning is not limited to experimental techniques but effectively includes content understanding and higher order thinking skills as reflected by the results here presented. As stated in the chapter introduction, research has seldom succeeded in providing this kind of evidence. The findings from this work show the desired “simple relationships between experiences in the laboratory and student learning” that have been advocated by others (Hofstein & Mamlok-Naaman, 2007).

Metacognitive instruction in this study was implicit; participants were not directly instructed about the object of assessment. It is believed that this approach facilitates
internalization of strategies since the changes come from within the students and are not seen as an external imposition. Participants developed a toolbox of relevant metacognitive skills as a way to be functional in the learning environment. In summary, this chapter presents evidence that supports the feasibility of promoting metacognition use in a laboratory cooperative environment that has been designed to require the exercise of metacognitive skills.

**Implications for teaching**

The conclusions drawn from this work do not only refer to the applicability and usefulness of *this* laboratory project. Their replication and consistency with other reports shed light about the possibilities of instruction in the chemistry laboratory. Two fundamental components of the intervention used are the intense social interaction and the environment conducive to the exercise of metacognitive skillfulness. The combination of these factors significantly promotes the development of problem-solving skills and learning. In the big picture, the evidence presented adequately shows the relationship between experiences in the laboratory and student effective learning. This can positively inform curricular development based on sound research evidence. Metacognition has the potential to be developed across a variety of social learning and teaching tasks (Yore & Treagust, 2006) many of which can take place in the chemistry laboratory, not necessarily as isolated interventions but as an underlying instructional constant.
Chapter One introduced the two fundamental questions that guided the development of this research project. The first one was concerned with the possibility of developing a multimethod to reliably assess the use of regulatory metacognition in chemistry. Before this research project was launched, no study that addressed such goal had been reported. The findings discussed in this work allow a quick answer to this first question: Yes, the multimethod combining the Metacognitive Activities Inventory as the prospective instrument and IMMEX as the concurrent instrument is a reliable method for the assessment of metacognition use in chemistry. The second question was a corollary of the first one and intended to determine the viability of enhancing regulatory metacognition use in chemistry by instructional interventions such as a collaborative paper and pencil activity and a cooperative problem-based laboratory project. The general development of metacognition had been researched extensively; only a handful of studies specifically tackled the question in the field of chemistry. However, in the absence of an appropriate assessment tool, effectiveness in accomplishing the goal had been evaluated using achievement outcomes in some cases, and subjective instruments in other. Direct assessment of metacognition use in chemistry using a large number of participants remained unfeasible. The second guiding question implicitly calls for the use of the multimethod developed in the first part of this project thereby giving to this old question a new approach. In short, evidence collected using the multimethod assessment
corroborates the fact that regulatory metacognition use can be enhanced by using instructional interventions. This conclusion was drawn from results in two different and independent studies (the collaborative metacognitive intervention and the laboratory cooperative problem-based project) and it is specific to chemistry problem-solving.

Six research goals established in Chapter One were foreseen necessary to accomplish the task of finding answers to the guiding questions. These goals were approached and achieved as described in Chapters III-VI. The following sections elaborate more on the answers offered above; they do also address the impact that the findings of this research may have on chemistry education and touch on possible new research directions.

**Assessment of Metacognition**

The lack of adequate assessment instruments was identified as a barrier for the advancement of research on metacognition. The research presented in Chapters Three and Four stems in response to the need for measures of this construct that are easy to use, time-efficient and reliable (Sperling et al., 2002; Veenman, 2005). A multimethod design, namely an across-method-and-across-time design was chosen after the convincing arguments made by Veenman (Veenman, 2005) regarding the potential of such a design.

The qualities of each instrument were demonstrated separately. The findings in Chapter Three led to the conclusion that the Metacognitive Activities Inventory is a robust and reliable instrument on its own. Additionally, face and construct validity were well supported. At this point it must be emphasized that the use of the MCA-I for the studies presented in Chapters Five and Six further established its construct validity. Both studies presented in those chapters had as purpose the enhancement of metacognition use
and awareness and the MCA-I effectively and consistently detected that desired change. This evidence was triangulated by the use of the second assessment tool, IMMEX, in both studies. These results, as the MCA-I’s ability to predict group differences and the inverse correlation of inversely coded inventory items, strongly support the inventory validity. Additionally, in all pre- and post-test instances, for both control and treatment groups, paired results were highly and significantly correlated making evident the robustness of the inventory.

The utilization of IMMEX to evaluate metacognition use (Chapter Four) is yet more significant since it constitutes a big leap in concurrent metacognition assessment. IMMEX circumvents many of the most cumbersome difficulties encountered with traditional concurrent assessment. By using IMMEX a large contingent of participants can be evaluated rapidly and using multiple performances for each one, individuals’ classification is researcher-independent which does away with potential bias, metacognitive skills are captured in a more naturalistic environment and in absence of observers thereby minimizing disturbance, and besides being automated, the entire process is time and cost efficient. The effectiveness of IMMEX technology in measuring regulatory skillfulness is very encouraging especially if the consideration is made that the problem used was not specifically designed for this purpose and that more accurate measures may be attained from more specific problem environments. The potential of IMMEX in the assessment of metacognitive skills needs yet to be further explored.

Chapter Four presents the convergence study between the two instruments. The instruments were proven convergent by analysis of the sound evidence collected in that
study. As in the case of the MCA-I, this evidence was strengthened by the “field use” of the multimethod. The MCA-I and IMMEX were proven convergent not only during the study done with that purpose but they also converged in the two independent studies addressing the effectiveness of instructional interventions. It is rather significant that both, the MCA-I and IMMEX, registered the same trend changes in use of and awareness about metacognition when the learning environment was modified in both additional studies. The consistency across these three independent studies is here underscored as strong evidence of construct validity and convergence evidence for the multimethod presented in this work.

**Instructional Development of Metacognition**

The similitude between the results obtained for both interventions (the short term paper and pencil collaborative metacognitive intervention discussed in Chapter Five and the cooperative problem-based project discussed in Chapter Six) is remarkable. Even though the ultimate objective of the interventions is the same—enhancing the use of metacognition—they are completely independent and their characteristics and approaches are dissimilar. The collaborative metacognitive instruction is not chemistry content related, it is shorter in duration (total task time is estimated to be less than 2 hours), it specifically and directly prompts participants about the components of regulatory skillfulness and it is well structured using a guided approach in the sense that it tells students, for example, to reflect or discuss about specific aspects.

The metacognition enhancement approach utilized in the cooperative problem-based project study is novel in that it is fully blended with instruction. As pointed out by
Georghiades (Georghiades, 2006) often researchers studying metacognition in science education have taught it as “a context-free general thinking skill, taking specially allocated time for this purpose”. The laboratory project is chemistry content based and relies on situated learning; it is of much longer duration (estimated on-task time is at least four 3-hour lab periods, plus three outside hours, totaling about 15 hours), it does not target specific aspects of metacognitive skillfulness, and it is only loosely structured.

The effects observed for both interventions are consistent between them (increased metacognition awareness and use) and in agreement with findings in previous reports by Cooper and collaborators who used IMMEX to investigate the effect of short term collaborative online problem-solving interventions, (E. Case et al., 2007; Cooper et al., 2008) and group use of concept mapping (Cooper et al., 2007; Cox, 2006). Other studies introduced in this work have used this ecological approach to develop metacognition and have arrived at similar conclusions. For example, Larkin (Larkin, 2006) documented the positive impact of collaborative group work on individual development of metacognition in five year old children. In her research approach, Larkin used verbal interaction analysis to track progress in metacognition processing and used a case study as her theoretical framework. Her subjects were observed monthly for a period of an academic school year. Case et al. (J. Case et al., 2001) concluded that their second year chemical engineering students showed metacognitive development in a course in which “developing metacognition was an explicit and important aim for the lecturer”. They described teaching strategies like collaborative learning, student centered learning, active learning, and promoted verbal interaction, argumentation, discussion and verbal
reporting. In addition, students were required to keep a journal that served twofold purposes: as a reflective activity and as a source of documentation to be later analyzed. The exposure to this embedded instruction lasted for the entire semester. Georghiades (Georghiades, 2006) used implanted brief metacognitive activities in his science instruction to Year 5 primary school children. Each activity lasted from two to six minutes, averaging six in each of the four 80-minute class periods utilized. The author used a quasi-experimental control treatment design and a content-test to assess the effect of the instruction on understanding. Based on his findings Georghiades recommends the inclusion of metacognitive thinking activities alongside the habitual instruction in science.

The evidence presented in this work is complementary to work done before by these and other authors. However, the methodological strengths and robustness of the studies here presented make its support to previous findings more relevant. The methodological approach used was strictly quantitative and data collection utilized a multimethod composed of two independent instruments, different in nature and administered at different times. The automated quality of the multimethod allowed the inclusion of large numbers of participants. It is also unique, and of utmost importance, that it directly quantified changes in the construct under study instead of relying on other quantifiable learning outcomes (i.e. achievement tests) or subjective qualitative observations. Effectiveness assessment did not rely on student evaluations or other surveys that directly address the intervention. Subjective aspects such as attitude, engagement, morale, or participation were not included as measures of effectiveness. For
example, in the case of the cooperative problem-based project study, the MCA-I did not ask students directly about the laboratory experience but measured a construct that for all practical purposes students did not see linked to the intervention. As part of their General Chemistry course, students worked on several different IMMEX assignments and from their perspective, Hazmat was just one more. Another aspect of relevance is the distance placed between researchers and participants; this responded to efforts of actively avoiding direct instruction of any kind that might bias students’ responses and performance, and/or researchers’ data interpretation.

The overarching purpose of this work was to explore the effectiveness of learning environments that were designed to promote the use of metacognition in chemistry problem-solving and thereby might improve chemistry learning, problem-solving and autonomous thinking. However, it was not its purpose to suggest the use of specific individual interventions but rather the creation of learning environments that embed strategies that have been identified to promote the practice of metacognition. Based on the findings from these studies and the revision of literature, meaningful and purposeful social interaction and reflective prompting seem to be the key promoters of the development of metacognition in the learning environments used. Learning environments that incorporate these promoters will improve the feasibility of students practicing their metacognitive skills; however, instructors should not be oblivious of the fact that learning is a complex process and influenced by other determinant factors such as motivation. An otherwise highly effective learning environment will be useless if the will to learn is not activated.
Admittedly, more queries of interest stem from this work than the questions answered. For instance, how could the influence of length of metacognitive instruction be measured? Would it be reasonable to assume that metacognitive skillfulness activated during brief instruction will be operative over a prolonged period of time? Is there a ceiling effect in the enhancement achievable through instruction? Are there gender determined factors that should be considered in the development of metacognitive instruction? Can qualitative methods be used to probe how metacognition enhancement occurs in the learning environments employed in these studies?

Metacognition, as any construct dealt with in Chemical Education Research, cannot be assigned properties of a physical quantity. Unfortunately but quite understandably, chemists, as physical scientists, risk falling in the trap of thinking in terms of *additivity* properties in relation to construct development. Paradoxically, this additivity stage has been shown to be a generator of misconceptions in chemistry learning (Talanquer, 2006; Talanquer, 2007) and science learning in general (Siegler, 1983). Uncovering misconceptions about metacognition held by chemistry educators and researchers may present itself as an interesting research topic.

Psychometric assessment, as chemical analysis methods, is constrained to the limitations of the instrument employed and to the characteristics of the method, for example, range of operation, detection limit, signal saturation, and sensibility. The multimethod employed in these studies should be better understood as a means to detect when instructional strategies work towards metacognition enhancement but the absolute values of the measurements should not be overloaded with significance.
Mixed methods research may constitute a proper way to gain a deeper understanding of the processes that are activating students’ use of metacognitive skills. A sequential explanatory design using a phenomenological study following the quantitative data gathering seems like a reasonable approach. Student interviews combined with systematic observation may be a path to insightful information that is undetectable by quantitative methods.

**Implications for Teaching**

The multimethod assessment of metacognition developed for this project is in direct response to Veenman’s assertion that “*little or no correspondence between prospective and retrospective statements on the one hand, and actual, concurrent behavior on the other*” has been revealed (Veenman, 2005). Its intent is to contribute to fulfill the need for multimethods and to give access to a reliable, efficient and rapid assessment instrument. The multimethod assessment of metacognition constitutes a strong research tool that can be further used and modified to investigate the effectiveness of diverse pedagogical protocols. But it does also have multiple immediate uses for the practitioner. Results obtained from the assessment can inform teachers’ practice. As mentioned previously, metacognition use and awareness can be part of students’ profiles and considered as part of course planning. Individuals who overestimate and underestimate their metacognitive skills can be readily identified, and tailored interventions may be implemented. Knowing the metacognitive ability of students may allow teachers to make informed decisions regarding collaborative and cooperative grouping for habitual instruction as well as during interventions.
The convergence between the two independent pedagogical protocols presented in this study clearly supports the assertion that it is the thoughtful practice of metacognitive skills that benefits students. Findings support the usefulness of combining purposeful social interaction (collaboration or cooperation) and prompting in developing general awareness and use of regulatory metacognition. Chemistry teachers can take advantage of the collaborative metacognitive intervention as presented in this study, or modify it to fit their instruction. Hopefully, these findings will promote the adoption of the cooperative problem-based laboratory model or similar instruction environments. In a broader scope, this work may inspire teachers to blend in activities that include prompting and social interaction during instruction, and to move away from exclusive traditional lecturing. This impact may be of more relevance in laboratory instruction where skeptical teachers might have needed more evidence to move away from traditional cookbook-type laboratories.

As with cognitive skills, the use of regulatory skillfulness may deteriorate in the absence of continuous practice. Skillfulness gains related to a single event should not be expected to solve the education quandary and produce independent thinkers and autonomous learners *ipso facto*. It is hoped here that the contributions from this work will inspire teachers and researchers alike to question and assess their instructional methods and encourage them to participate of developing an evidence-based curriculum. Metacognitive instruction may not be the solution to all of contemporary education’s problems but findings show it represents a step forward in the right direction.
Appendix A: TA Instructions for the Administration of Instruments

Department of Chemistry
Chemistry Education
Research

General Information for Teaching Assistants

CH 101L

IMMEX is part of the lab assignments.
General methodology and implementation of Chemical Education research activities.  
CH 101 L

The success of our data collection relies heavily on the assistance from the instructors and teaching assistants. We do appreciate your collaboration which in turn is part of your responsibilities as a TA in our general chemistry program. In this document you will find general information regarding the assessment instruments we will use this semester and the methodology and schedule of activities. Please, feel free to contact us if you want more in-depth information or if you have comments you want to share.

Description of instruments

**Group Assessment of Logical Thinking, GALT**

This test consists of 20 multiple-choice items and two short answer questions; it is a paper-and-pencil test. The multiple choice questions are paired, the first component of the pair asks for the most appropriate response to a given scenario, the second one inquires students upon their reason to choose the answer given. Credit is given only if the student answers both questions in the pair correctly. GALT assesses student’s proportional reasoning and abstract thinking abilities which are considered relevant to assess scientific aptitude. According to the score obtained, students are classified as concrete, transitional and formal. Concrete students have difficulty thinking abstractly and using proportions, formal students manage these abilities well, and transitional students have intermediate abilities.

Administration of this test usually takes less than 15 minutes, and students are asked to use their CU id.

**Metacognitive Activities Scale, MCA**

This is a 27-item survey designed by the research group. Its objective is to determine the extent in which students use activities related to planning, monitoring and evaluating as part of their problem solving strategy. Participants are expected to answer based on their habitual performance and not specifically related to a given problem or situation. It uses a 5-point Likert scale ranging from “Strongly Disagree” (1) to “Strongly Agree” (5). It is administered using scantrons to collect data, and students are required to use their Clemson ID Number. Usually, completing the instrument takes about ten minutes. The survey will be administered twice in the semester to observe changes in students self reported use of metacognition as consequence of instruction and of interventions.

**IMMEX assignments**
IMMEX stands for Interactive Multi-Media Exercises; it is a web-based interactive environment which presents students with real problems. As students devise a path to solve the problem, information about the items they have chosen to use, their sequence and the time they are used is collected. Also the correctness of the answers is recorded. These pieces of information are used to partially reconstruct the students’ solving strategy.

The first IMMEX assignment is called Hazmat, it is a qualitative inorganic analysis problem. This problem set is tightly related to the first lab project and will be assigned immediately after students give their oral presentation for this project (5th week). It will be due by 9 am the same day they have lab the week after (6th week). Students will have been in contact with the content knowledge to solve the problem set. Participants in “no pre-test” groups (TnpT and CnpT) will be assigned a different problem set (Periodic Trends). The second IMMEX assignment will be the same for all the sub-samples: Hazmat. It will be assigned the same week the intervention (see below) is finished (8th week) and due the same day the lab meets the week after (9th week). Using Hazmat for the first and second IMMEX assignment will allow evaluation of strategy use modifications provoked by instruction and by the intervention.

The third IMMEX assignment is called “Convertible”, it will be assigned week number 11 and due week number 12.

For each assignment, participants must work on 6 cases. Each assignment will count 5 points; 10 points will be awarded for participation which includes the completion of the surveys, the GALT test and the intervention. Total IMMEX points: 25.

Problem Solving Activity

The objective of this intervention is to raise the students’ awareness of and to promote the use of metacognition in problem solving. It uses small group activities to engage students in situations which require reflection upon strategy use. It also contains a series of prompts, questions and short comments to guide students through the reflection of their problem solving strategy development and use. It will be administered in three weekly sessions of approximately 30-45 minutes. The first session is done in the lab and uses small groups; there is little supervision and no lecturing or instruction! The situation or problems used are non-chemistry related. The second session is a large group discussion; it uses some lecturing and a combination of non-chemistry and chemistry related situations or problems. The third session is conducted in the lab or given as homework, it requires the solution of a chemistry related problem, in group and individually.

Only half of the students undergo the intervention. Once relevant data have been collected, the other half will be given a shortened version (2-sessions) in a take-home format.
MCA-Inventory administration
Instruction for CH 101 L TA’s

Only half of the sections will be administered the MCA-Inventory during the second week the labs meet.

Procedure:

(1) Verify that your section is doing the inventory, for this purpose, check the list in the stockroom.
(2) Administer the survey at the beginning of your lab. If you consider a student is late and does not have a valid excuse, feel free to not give him/her the survey. They will then lose the IMMEX participation points.
(3) Folders, scantrons, instructions and manila envelopes will be in the stockroom. (Look for a cart in the back of the stockroom.)
(4) PLEASE READ THE INSTRUCTIONS TO THE STUDENTS (see below)
(5) Usually, students need about ten minutes to complete the survey.
(6) Please, try to keep them on task. No multitasking, no talking, absolutely no surfing the internet.
(7) As they turn in their scantrons, check they bubbled in all the necessary information. If there is anything missing, do not bubble it for them, have them do it.
(8) Place all scantrons in a labeled envelope. Take back to stockroom.

I will be walking through your labs doing student observations.
Thanks for your help and cordial collaboration.

Santiago Sandi-Urena

Instruction to the students

Following, you will find statements that may or may not describe actions you take while solving problems. All the items refer to your typical performance while you work on solving chemistry problems, not to your feelings or convictions.

- This assignment is part of your grade.
- Bubble in your name, CU ID number, course, and lab section.
- Do not over-elaborate the meaning of the statements.
- If you do not understand an item, leave it blank.
- If you understand an item but have no strong opinion, mark the letter C.
- Read each item carefully and bubble the letter that corresponds to your experience.
Problem Solving Activity administration
Instruction for CH 101 L TA’s

Only selected sections will be administered the Problem Solving Activity during the coming week.

Procedure:

1. Verify that your section is scheduled to work on this assignment, for this purpose, check the list in the stockroom
2. Administer the Problem Solving Activity at the beginning of your lab. If you consider a student is late and does not have a valid excuse, feel free to not give him/her the materials. Have them contact us directly in case they have questions.
3. Folders, scantrons, instructions and manila envelopes will be in the stockroom. (Look for a cart in the back of the stockroom.)
4. PLEASE READ THE INSTRUCTIONS TO THE STUDENTS (see below)
5. Usually, students need about 45 minutes to complete the activity.
6. Please, try to keep them on task. No multitasking, absolutely no surfing the internet.
7. This is a collaborative activity and students are expected to interact amongst themselves. Interaction between members of different teams is fine as long as they remain on task and are not disruptive to others.
8. Place all booklets in a labeled envelope. Take back to stockroom.

I will be walking through your labs doing student observations.
Thanks for your help and cordial collaboration.

Santiago Sandi-Urena

Instruction to the students

Following you will work on a Problem Solving Activity. This activity counts towards your grade.

• The first component to this assignment requires students to work in teams of two.
• Turn in only one set of answers for the team.
• The second component is an individual homework assignment. Each student needs to turn in his or her homework next week at the beginning of the laboratory
• You have 45 minutes to complete the team component of this assignment.
• Please read the instruction on the booklet carefully.
Appendix B: Collaborative Metacognitive Intervention

Department of Chemistry
Chemistry Education
Research

Problem-Solving Exercise

This activity is part of your lab assignments.

Instructions:

1. You must work in teams of two students unless your instructor tells you otherwise.
2. Discuss each step with your partner. Grading is based on the completeness of the answers.
3. The team must complete all the items in this exercise.
4. Part VI “Final Problem” must be turned in individually. There are two copies of this section attached to this document.
5. This is a timed exercise, use your time wisely.

Team members: ___________________________________ Lab section: ________
____________________________________________
____________________________________________

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Part I

INITIAL PROBLEM

Read the following problem carefully and try to solve it the best you can.

“Barbara asked me to bring her a pair of stockings from her bedroom. Unfortunately, the bedroom is dark and the light is not working. I know there are black socks and brown socks in the drawer, mixed in a ratio of 4 to 5. What is the minimum number of stockings I will have to take out to make sure that I have two stockings of the same color?”

If needed, you may use the space given below to solve the problem.

Please, enter your answer here, and then move on to the next page: __________________
Please, answer the following questions. Be concise but observe that in some cases, an explanation is expected and yes or no will not necessarily suffice.

1. The commonly accepted answer to this problem is “three”. Did your group succeed in solving the problem correctly?  
   (Yes)  (No)

2. Do you think that your group identified the problem correctly?  
   (Yes)  (No)

3. If your group did not identify the problem correctly, what do you think was the cause? (Check all that apply):

<table>
<thead>
<tr>
<th>Lack of ability</th>
</tr>
</thead>
<tbody>
<tr>
<td>We assumed we knew what was being asked.</td>
</tr>
<tr>
<td>Lack of necessary knowledge</td>
</tr>
<tr>
<td>Unknown or difficult vocabulary</td>
</tr>
<tr>
<td>Lack of capacity to reason</td>
</tr>
<tr>
<td>Misunderstanding, the team understood something different</td>
</tr>
<tr>
<td>Lack of attention</td>
</tr>
<tr>
<td>The question is confusing</td>
</tr>
<tr>
<td>The problem is too difficult</td>
</tr>
<tr>
<td>Inadequate amount of time put in identifying the exact problem</td>
</tr>
<tr>
<td>The group approached the problem mechanically, without much reasoning</td>
</tr>
<tr>
<td>This is a tricky problem, the question is misleading</td>
</tr>
<tr>
<td>The statement is not well-written</td>
</tr>
<tr>
<td>The group is not good with math</td>
</tr>
<tr>
<td>The group did not make a real effort to understand</td>
</tr>
<tr>
<td>The question seemed similar to previously encountered problems, we did not analyze the question well enough</td>
</tr>
<tr>
<td>Other (specify):</td>
</tr>
</tbody>
</table>

4. Approximately, how many times did your group read the problem statement before actually starting work on the solution?  
   0  1  2  3  4  more than 4 times.

5. Do you think your group started working on the solution having a clear understanding of the problem?  (Yes) (No)
6. If you answered “no” to question (5), what could be the reason(s)?

7. How many times did you change your answer? Circle as appropriate;
   
   0  1  2  3  4  more than 4 times.

8. What were the reasons for changing your answer? (Check all that apply):

   Initially, the team was just guessing  
   The number was clearly too large!  
   The result was right the first time, no change was needed  
   The members of the team did not agree on the right answer  
   The result was too small!  
   The team was very uncertain about the result  
   A mistake in one of the calculations was found  
   The team realized the problem had not been understood properly.  
   Members of the team reviewed the result to see if it made sense.  
   The result seemed strange  
   Members of the team could not agree on a single result.  
   No change made, the team was sure the result was right, although later it was found to be wrong  
   We reviewed the solution and came up with a different result  
   Other (specify):

9. List three aspects your group could change to be more effective and efficient solving problems like the one given.
   1)  
   2)  
   3)  

10. In a scale from 0 to 10, what grade would you give to the solution provided by your group?
   
   0  1  2  3  4  5  6  7  8  9  10
   Extremely bad     Extremely good

11. Why would you assign your group that grade?
   Answer:
Part II
Can any student become a better problem solver?

There are different ways to characterize problems. One way is to assume a problem contains: givens, goal, and obstacles.

A. The givens are the elements, their relationships and the conditions known initially. Everything that helps describing the initial state or condition.
B. The goal is the desired solution or outcome of the problem; it can be seen as the desired final state.
C. The obstacles are the properties of the problem and the characteristics of the problem solver that make it difficult to reach a solution.

12. Which one of the above mentioned aspects can be changed by the student? Why?

13. Do you, as a team, believe that any student can become a better problem solver? Why?

14. For the problem your team solved, list two characteristics of the problem solvers that can be considered as obstacles:

1) 
2) 

15. List three things that would help anyone becoming a better problem solver:

1) 
2) 
3)
As obvious as it may sound, one must recognize there is a problem before one can start solving it! One must also identify the right problem and identify it correctly, too. Sometimes, there are givens that are not necessary for the efficient solution of a problem. A good problem solver sorts out the information and makes a mental or written record of those elements critical or relevant.

16. State the “goal” for the previous problem?

17. List one piece of information that was not necessary to solve the problem and one that was relevant?

Information not necessary:

Information relevant:

18. Did your team try to use any piece of information which was not really necessary to solve the problem? Which piece of information was it?
Part IV
PLANNING

Ineffective problem solvers jump prematurely to a solution. No matter how complicate or simple a problem, it is always necessary to do some planning. The depth and complexity of planning depend in part on the problem itself. Sometimes, one needs to write a sequence of steps or several equations to be used, intermediate goals and calculations. Sometimes the plan is completely mental, brief and simple.

Though always necessary, planning does not only depend on the problem but on the problem solver, too. The amount and the form of planning vary from individual to individual and it is imperative to find the best planning type one can use.

19. Read the following statements and mark yes, no or n.a. (not applicable):

<table>
<thead>
<tr>
<th>The team answered the problem inappropriately fast</th>
<th>(yes)</th>
<th>(no)</th>
</tr>
</thead>
<tbody>
<tr>
<td>The team used some sort of representation (drawing, diagram, flow chart, etc)</td>
<td>(yes)</td>
<td>(no)</td>
</tr>
<tr>
<td>The team devised a plan</td>
<td>(yes)</td>
<td>(no)</td>
</tr>
<tr>
<td>Was the plan complex?</td>
<td>(yes)</td>
<td>(n.a.)</td>
</tr>
<tr>
<td>Was the plan purely mental?</td>
<td>(yes)</td>
<td>(n.a.)</td>
</tr>
<tr>
<td>Was planning sufficient?</td>
<td>(yes)</td>
<td>(n.a.)</td>
</tr>
<tr>
<td>The team thinks planning is not indispensable.</td>
<td>(yes)</td>
<td>(no)</td>
</tr>
</tbody>
</table>

20. Do you think that having been more reflective would have helped your group find the correct solution? Explain briefly.

21. Do you think that using a representation did improve/would have improved your performance? Explain briefly.

22. In the teaching profession there is a frequently used principle called “The Five P’s”: Proper Planning Prevents Poor Performance. What do you think of this expression?
Part V
EVALUATING

Evaluating the process one uses to reach a solution is important. By doing so, one knows one is not off track and it makes the whole process more efficient. Let’s pretend you are going to a job interview. You are using a map to get to this place to which you have never been before. Your directions read “after the gas station, go straight for two miles and turn right at the Courthouse”. If you pass the gas station and after driving straight for 5 miles you find no Courthouse, wouldn’t you know there is something wrong with your driving plan? Most probably, you would stop, re-consider the situation, make adjustments to your plan, execute the changes and see if it works this time! Or would you keep driving just because that is what the plan is?

Evaluate the outcome, if it makes no sense, it cannot be good! For example, if the goal of a problem is finding the weight of a car, and one arrives at the answer: “the car weighs one million pounds”… most certainly something is not correct with the solution.

Let’s say a group produced the following answer to the problem given initially: “The minimum number of stockings needed to take out to be sure one has two stockings of the same color is 8”.

23. Does this answer make sense? Why/why not?

24. Would your solution for this problem have been different if the room had not been dark?

25. Do you, as a team, believe that any student can become a better problem solver? Why?

26. List the best three things that you think could help anyone becoming a better problem solver:

1) 
2) 
3)
Part VI

FINAL PROBLEM
YOU MAY DISCUSS AS A GROUP, BUT EACH INDIVIDUAL
MUST TURN IN
HER OR HIS ANSWER SEPARATELY
(THERE ARE TWO COPIES OF THIS PAGE ATTACHED)

Name: ____________________________________________ Lab Section: ___________

Choose and solve **only one** of the following problems. Practice any new skill you may
have learnt from the previous pages, for example, identifying the goal, sorting out
relevant information, using graphical representations, planning and evaluating, etc.

Problem #1 “A car in Philadelphia starts toward New York at 40 miles an hour. Fifteen
minutes later a car in New York starts toward Philadelphia—90 miles away—at 55 miles an
hour. Which car is nearest Philadelphia when they meet?”

Problem #2 “George wants to fry 3 eggs as quickly as possible. Unfortunately, his pan
only holds two eggs and each egg takes 2 minutes a side to cook. What is the shortest
amount of time in which George can fry his 3 eggs?” (Yes, George wants both sides of
his eggs cooked!)

1) Identify and define the problem: state the problem and the goal in your own
words.

2) According to the goal, what information given is not relevant and might not be
used?

3) What information is relevant and will be used?

4) Planning: devise a brief plan to solve the problem.
5) Make a drawing or scheme that represents the initial conditions and the final conditions for this problem.

6) Can you see the answer from your drawing?

7) What is your answer to this problem?

8) Does your answer make sense? Why?

9) Was the solution to this problem obvious from the beginning or did your representing and planning help you in understanding and solving the problem? Explain.

10) Things are not always what they seem, and too often one is so very over-confident that does not check the process and answers. The correct answer for problem #1 is “neither one, both cars are at the same distance from Philadelphia”. The correct answer for problem #2 is “The shortest amount of time George needs to fry his 3 eggs is 6 minutes”. Knowing the answer, can you explain the solution? (yes) (no)

11) From the previous experience, how would you rate yourself as a problem solver?

   0 1 2 3 4 5 6 7 8 9 10
   Extremely bad Extremely good

12) Do you think you can transfer these problem-solving skills and practice to Chemistry problems? Explain briefly.

13) Please, write any comments your may have about this problem-solving exercise.
Part VII

Name: ____________________________________________ Lab Section: ___________

In a recent exercise, a majority of students failed to correctly solve a problem which can be classified as very simple and whose answer can be produced within seconds and without any calculation. However, most students performed unnecessary calculations.

Read the problem and look at the drawings below.


Initial state:

__________________________________________________

Philadelphia                                                                                                           New York

Which car is nearest Philadelphia when they meet?”

Final state:

__________________________________________________

Philadelphia                                                                                                           New York

Once the problem is correctly identified, the solution becomes evident: they are at the same location and therefore, at the same distance from Philadelphia (or from any other place!).

The same obstacles that students identified as keeping them from efficiently solving this problem are affecting students’ performance in more complex General Chemistry problems.

Most students overwhelmingly agreed upon the fact that the characteristics from the problem solver may turn into obstacles for the solution, but luckily they also agreed they can be changed!
This is a summary of the reasons which, according to the students’ responses, caused the low solution rate. Read them and check all that you think apply to your last week’s team:

The team did not identify the problem correctly:
___ Failure to establish the goal of the problem
___ Use of a mechanical approach
___ Over-confidence
___ Sense of knowing what the goal was without inferring it from the problem itself
___ Students assumed conditions which were not given in the statement but were recalled from “similar” problems

Overall lack of planning:
___ Lack of using a representation (diagram, scheme, drawing)
___ Work was started without fully understanding the problem
___ Work was started without having a plan (research shows that students who spend more time planning are more successful than no-planners)
___ Importance or relevance of information was not questioned.

Poor monitoring of solution process:
___ During solution, the team did not stop to reconsider if strategy was taking them to the answer (plans can be adjusted, changed, improved or discarded)
___ Little verification of the solution path making sense

Lack of evaluation
___ Even though the result made no sense, the team did not notice it and would have missed the opportunity to make corrections had it not been because they were given the correct answer.

**An electronic copy of this summary will be sent to all students to use as needed.**

Please use the following scale to rank your degree of agreement with the statements below.

<table>
<thead>
<tr>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strongly disagree</td>
<td>disagree</td>
<td>neutral</td>
<td>agree</td>
<td>strongly agree</td>
</tr>
</tbody>
</table>

The two-week problem-solving exercise has helped me improved my problem solution skills:

| 1 | 2 | 3 | 4 | 5 |

I would like to participate in a four 90 min section workshop to develop my general problem-solving skills.

| 1 | 2 | 3 | 4 | 5 |

Currently, I am a good problem solver:

| 1 | 2 | 3 | 4 | 5 |
Appendix C: Informed Consent Form

CONSENT TO PARTICIPATE IN A RESEARCH STUDY

DEVELOPMENT OF TECHNOLOGY BASED ASSESSMENTS IN CHEMISTRY

Study to be conducted at: Clemson University, Chemistry Department

Principal Investigators: Melanie M. Cooper  656 2573
Charles T. Cox
Terry L. McAlister
Guillermo S. Sandi-Urena
Todd A. Gatlin

INFORMATION:

You are invited to participate in a research study. The Institutional Review Board (IRB) of Clemson University has reviewed this study for the protection of the rights of human subjects in research studies, in accordance with federal and state regulations. However, before you choose to be a research participant, it is important that you read the following information and ask as many questions as necessary to be sure that you understand what your participation will involve. Your signature on this consent form will acknowledge that you received all of the following information and explanations from the principal investigator (or his/her designated representative), and have been given an opportunity to discuss your questions and concerns with the principal investigator or a co-investigator. Additionally, should you have any questions regarding your rights as a human participant, please do not hesitate to contact a member of the IRB at 864-656-0636.

PURPOSE:

This study involves research into how students learn to solve problems. Approximately 1300 students per semester will be involved in this research.

PROCEDURES:

You will work a series of web based chemistry problems approximately four times during the semester. The program you will be using keeps track of the information you use to solve the problems and allows us to compare your strategies with those of your peers. Part of the information collected will be in the form of surveys and/or scales administered before or after your working on the web based problems. Random short interviews may be used to collect additional information. Your approximate time commitment will be four (4) hours per semester.

POSSIBLE RISKS:

This project is minimal risk research. Any statements or actions on your part will not be identified by your name or any other identifier to anyone outside the project, and your participation in this project will be held in confidence, however results of the project may be published. Any results from this project will not contain information by which you may be identified.
EXCLUSION REQUIREMENTS:

Students under 18 years of age will not participate in this research study.

POTENTIAL BENEFITS:

The potential benefits from this research include: improved problem solving skills and improved content mastery. It is not possible to predict whether or not any personal benefit will result from your participation in this study. You understand that the information that is obtained from this study may be used scientifically and may be helpful to others.

VOLUNTARY PARTICIPATION:

Participation in this study is voluntary. You may refuse to participate or withdraw from the study at any time. If you do not wish to participate, you may still be asked to complete the problems as part of the assignments in the lab. Data will not be collected on students who elect not to participate. If you refuse to participate or withdraw from the study at any time, you will not be penalized or lose any benefits and your decision will not affect your relationship with this institution. The investigator may withdraw you from the study at any time. If this is done it will not affect your grade. You will be informed of any significant new information regarding this study that may affect your willingness to continue in this study.

CONFIDENTIALITY:

The records of your participation are confidential. The investigator will maintain your information, and this information may be kept on a computer. Study information or data may be examined by the Institutional Review Board of Clemson University and various federal regulatory agencies. This study may result in scientific presentations and publications, but steps will be taken to ensure you are not identified by name.

QUESTIONS:

For more information concerning this study and research-related risks or injuries, you may contact the Principal Investigator (see first page for identifying information). You may also contact a representative of the Institutional Review Board of Clemson University for information regarding rights of participants involved in a research study.

CONSENT

I have been given an opportunity to ask questions about this study; answers to such questions (if any) have been satisfactory. In consideration of all of the above, I give my consent to participate in this research study. I acknowledge receipt of a copy of this informed consent statement.

PARTICIPANT'S SIGNATURE: ________________________ DATE: ___________

PARTICIPANT’S PRINTED NAME:________________________________________

Please sign here if you choose NOT to participate: _________________________
Project 11: Identification, Properties and Synthesis of an Unknown Ionic Compound.

Your group is employed by the EPA (Environmental Protection Agency) as analytical chemists. An unidentified compound has been discovered in a land-fill in your home town, and your group has been given the task of investigating it. Obviously you will want to identify the compound, but this is not the only thing you will need to do. It will be very important to the people of the area to know the properties of the compound, both chemical and physical, so that you can make predictions as to how it might behave. For example, if you know the solubility of the compound you will be able to give some indication of whether the compound will leach out of the landfill during heavy rain. If you know what kind of reactivity the compound has you could make some predictions on the safe disposal and the longevity of the compound. If the compound is not very reactive it might sit in a landfill for a long time. If the compound is very reactive it may not be as long lived, but it may react to produce something more toxic or difficult to dispose of. Therefore, it is very important that you amass as much information about the compound as you can.

GOALS

1. Identify the unknown compound.
2. Discover as many chemical and physical properties of the compound as you can.
3. Devise two syntheses of the compound, and compare them for cost effectiveness, safety and potential yield of compound.

You will be given five grams (no more) of the compound; you will not know the identity of the compound, nor will you be given any other information about it.

Safety Notes:

- Be sure to consult the MSDS for any compound that you work with.
- All of the compounds that you will work with in this project are Generally Recognized As Safe, but normal safety precautions should be observed.
- Any excess reagents solutions or waste materials may be disposed of by diluting the solutions and pouring down the drain unless otherwise instructed by your laboratory teacher.
In order to help you identify your unknown compound, samples of known compounds will be available in the laboratory. Use only what you need to compare with your unknown sample in tests. 

The following are some hints and ideas of possible lines of investigation for your project, however, the list is not all inclusive and you may have other possibilities which are equally valid.

1. What solvents is your compound soluble in? What are the relative solubilities in different solvents? How will you measure solubilities? What kind of information do your results reveal about the nature of your compound? What generalities can you make about the solubility of your compound and that of other known compounds available in the lab?

2. What ions are present in your compound? How will you find out? What resources are available to you to find and learn the techniques you will need?

3. Is your compound an electrolyte? How will you find out? How does it compare to other compounds available in the lab?

4. Does your compound have acidic or basic properties? How will you find out? Will you make quantitative measurements of the acidity/basicity?

5. What compounds does your unknown react with? How did you know a reaction took place? What did you observe?

6. How will you prepare your compound? (Do not forget about stoichiometry, theoretical yield and percent yield.) Is there more than one way to make your compound? What are the relative merits of the different methods? Do not forget safety and cost effectiveness in your deliberations.

In order to make your task feasible within a reasonable time frame, we will restrict the identity of your unknown compound to one of the following:

- NaCl  KCl  Na\textsubscript{2}SO\textsubscript{4}  CaCl\textsubscript{2}  MgSO\textsubscript{4}
- Na\textsubscript{2}CO\textsubscript{3}  K\textsubscript{2}SO\textsubscript{4}  KNO\textsubscript{3}  Ca(NO\textsubscript{3})\textsubscript{2}  MgCl\textsubscript{2}
- NH\textsubscript{4}Cl  (NH\textsubscript{4})\textsubscript{2}SO\textsubscript{4}  CaCO\textsubscript{3}  MgCO\textsubscript{3}  CH\textsubscript{3}CO\textsubscript{2}Na

Samples of these compounds will be available in the lab for you to test your hypotheses and compare with your unknown. 

**When using a technique for the first time, use samples of known compounds from those available to practice before you use up a sample of your unknown.**
Techniques you may need to learn or review

- Preparing a solution (qualitative)
- Preparing a solution (quantitative)
- Measuring solution conductivity
- Analysis of ions (qualitative)
- Analysis of ions (quantitative)
- Filtration of solid
- Titration

Analysis of an Unknown Compound

Pre-Lab Organizational Questions:

1. Outline a procedure for finding the solubility of your compound. What solvents will you use?

2. Outline a procedure for finding the quantitative solubility of your compound in water.

3. Outline a procedure for determining the conductivity of your compound. What solvent should you use for this test? If your solution conducts electricity what does that tell you about the compound?

4. What tests will you perform to find out what anions are present in your compound?

5. What tests will you perform to find out what cations are present in your compound?

6. How will you use the known compounds that are out in the lab to help you find the identity of your unknown compounds.

7. Write a preliminary plan for your experimental procedure. Indicate what each person in your group will do next week. Remember that all tests should be run in duplicate (at least).

Post lab questions week 1

1. What is the identity of your unknown? (if you have not yet identified it – give the possibilities)

2. Describe the experiments you carried out to determine the identity of your compound. How did each experiment lead to your identification?
3. Look up the MSDS for your compound and record the LD50 and the safety precautions that should be used when handling the compound. What does an LD50 tell you?

4. Next week you need to make sure that your identification is correct. There are authentic samples of all the possible compounds available. You need to make a solution of your compound and a solution of an authentic sample and compare their reactivity. What kind of reactivity do you expect for your compound? (Is it acidic or basic? Will it react to give a precipitate? etc.)

5. Give five examples of reactions (neutralization, double displacement, etc.) that you can carry out next week with your compound (both your sample and the authentic sample) to investigate its reactivity and confirm its identity. Write out the expected reactions and the products you expect to see, if any. (Remember that a negative result can still give you information)

6. One of the techniques you will need to learn is vacuum filtration – check out the technique in your lab manual or other resource and then give a brief description below.

7. Write a preliminary plan for your experimental procedure. Indicate what each person in your group will do to solve the problem, and what data they will record.

Post-Lab questions week 2

1. Give the results of the five (or more) reactions that you carried out to confirm the identity of your compound. Give a brief summary of the reactivity shown by your compound. How did these reactions serve to confirm the identity of your compound?

2. In order to be sure that your identification of the compound is correct you will need to devise a method that will give a quantitative analysis of the compound. How would a quantitative identification differ from a qualitative identification?

3. Using today’s results, what features of the compound could you use to give rise to a quantitative analysis? For example: can you react your compound with something that would give an insoluble salt, does your compound have acidic or basic properties? (Review quantitative analysis in your lab manual or other resource)

4. Remember that quantitative analyses should be run in triplicate to give accurate results. Outline the procedure you will use to do this.
5. Outline the calculations you will use to prove the identity of your compound. (you don’t need to put numbers in – just show the conversions you will do.

6. How will the results of these calculations confirm the identity of your compound?

7. Write a preliminary plan for your experimental procedure. Indicate what each person in your group will do to solve the problem, and what data they will record.

Post-Lab questions week 3
1. Outline three possible synthesis reactions of your compound. – Give the chemical reactions.

2. Which reaction is the “best”? What criteria are you using? (Safety? Cost? Environmental impact?) Discuss each criterion.

3. Give a step by step outline of the experimental procedure you will use to synthesize 5 grams your compound. (Be specific)

4. What laboratory techniques will you use during your synthesis?

5. Outline the calculations you will use calculate the % yield of your synthesis. (you don’t need to put numbers in – just show the conversions you will do.)

6. How could you prove that you have synthesized what you intended?
REFERENCES


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