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RESEARCH REPORT

Enhancement of Metacognition Use and Awareness by Means of a Collaborative Intervention

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Current views on metacognition consider it a fundamental factor in learning and problem-solving which in turn has led to interest in creating learning experiences conducive to developing its use. This paper reports on the effectiveness of a collaborative intervention in promoting college general chemistry students' awareness and use of metacognition. The intervention starts with a cognitive imbalance experience as a trigger for metacognitive reflection, which is then followed by reflective prompting and peer interaction. A quasi-experimental control and treatment design with 537 and 464 participants, respectively, was implemented. Assessment of metacognition was accomplished by using a multi-method instrument that consists of a self-report (Metacognitive Activities Inventory, MCAI) and a concurrent, web-based tool (Interactive Multimedia Exercises, IMMEX). IMMEX has been shown to allow rapid classification of problem solvers according to their regulatory metacognitive skills. Compared to the control group, the treatment group showed a significant increase in metacognition awareness, as evidenced by the MCAI, increased ability in solving non-algorithmic chemistry problems of higher difficulty, and with a higher per cent correctness (IMMEX). These findings are consistent with an overall increase in the use of regulatory metacognitive skills by the treatment group. We propose that the meaningful, purposeful social interaction and the reflective prompting instantiated by the intervention act as promoters of metacognition development. It is of particular relevance that these factors are not exclusive to the intervention employed here and can be embedded by practitioners in their instruction.

Keywords: *Chemistry education; University; Assessment; Learning environment; Quantitative research*

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Introduction

The term metacognition was originally coined by Flavell (Yore & Treagust, 2006) in the 1970s who described it as "knowledge and cognition about cognitive phenomena" (Flavell, 1979). At first, such description may seem categorically simple; however, as pointed out by Thomas, Anderson, and Nashon (2008) despite the considerable amount of research on metacognition and its impact on our understanding of learning, there is no clear consensus in the definition of the construct and its relationship with other concepts like self-regulation. Numerous and sometimes overlapping definitions are encountered in literature (Kauffman, Ge, Xie, & Chen, 2008; Schunk, 2008; Thomas et al., 2008), but probably the most common description for metacognition remains "knowledge and regulation of one's own cognitive system" (Brown, 1987, p. 66). For research purposes, we subscribe to the theoretical framework that identifies two major components of metacognition: knowledge of cognition (declarative, procedural, and conditional knowledge) and regulation of cognition (or executive component) (Schraw, 2001; Schraw, Brooks, & Crippen, 2005; Schraw, Crippen, & Hartley, 2006; Schraw & Moshman, 1995). The former is often understood as metacognitive awareness and has received considerably more attention than the latter (Yore & Treagust, 2006), regulation of cognition, which comprises the repertoire of actions in which an individual engages while performing a task. Consistent with this framework, metacognition occurs when individuals plan, monitor, and evaluate their own cognitive behaviour in a learning environment (Ayersman, 1995) or problem space. The influence and relevance of metacognition in learning and problem-solving has been substantially demonstrated. Swanson (1990), for instance, showed that regardless of overall aptitude, higher metacognitive children outperformed lower metacognitive children, suggesting that metacognitive training may compensate for lower abilities. This view of metacognition departs from models that "view students' learning potentials as fixed, pre-determined, and beyond the salvation of any form of intervention" (Thomas et al., 2008, p. 1702). It is not surprising then that over the past decades, interest in instructional enhancement of metacognition use has surged (Blank & Hewson, 2000; Davidowitz & Rollnick, 2003; Desoete, Roeyers, & De Clercq, 2003; Georghiades, 2004), including the use of specific strategies in chemistry (Francisco & Nicoll, 1998; Rickey & Stacy, 2000; Schraw et al., 2005; Tsai, 2001). From the science education researchers' perspective, metacognitive skilfulness has been generally accepted as influencing the achievement of deeper understanding (Yore & Treagust, 2006) and helping the individual's transition from a dependent learning state to that of autonomous learner (Schraw et al., 2006). According to Schraw et al. (2006):

> 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. (p. 117)

It has been categorically asserted that "it is possible to improve knowledge, strategies, metacognition, and motivation via classroom instruction" (Schraw et al., 2005,

p. 640) and that a way to accomplish metacognition enhancement is by "creating learning environments where students are allowed to explain and defend their thinking, opinions and decisions" (Tsai, 2001, p. 972). Zion, Michalsky, and Mevarech (2005) have suggested that "metacognitive skills development is typically fostered by asking students to reflect on and explicitly monitor their learning performance" (p. 959). However, there seems to be little evidence of the concrete effects of specific instructional techniques on metacognitive skills, in part, because of the lack of adequate assessment instruments. Rather, it has been a common practice to create learning environments that are believed to be conducive to the practice of metacognition and then looking at performance or achievement parameters related to learning and efficacy in solving problems to evaluate the effectiveness of the intervention (Davis, 2003). 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. In our view, the assertion that the creation of metacognitive instantiations leads to metacognition enhancement requires supporting evidence. Otherwise, this stance may be as valid as the teaching trap that assumes that learning occurs whenever lecturing takes place.

The need for developing appropriate assessments to evaluate the effectiveness of interventions has been argued by Schwartz, Bransford, and Sears (2005). Sears and Schwartz (2007) have stated that "the field of the learning sciences has spent a good deal of time creating instructional treatments that cause learning, but less time developing measures of those treatments" (p. 16). Despite its importance, the study of metacognition has been slowed by the lack of simple, rapid, and automated assessment tools. So far, most of the evidence used in research on metacognition have been derived from self-report measures from participants, for example, the Motivated Strategies for Learning Questionnaires, MSLQ (Pintrich & Smith, 1993), the Learning and Study Strategies Inventory, LASSI (Weinstein, Schulte, & Palmer, 1987), and in German language the Lernstrategien im Studium, LIST, designed by Wild and Schiefeles in 1994 (Spoerer & Brunstein, 2005) and the Kieler Lernstrategien-Inventar, KSI, introduced in 1992 by Baummert, Heyn, and Koeller (Spoerer & Brunstein, 2005). However, these instruments have seldom investigated the construct within the frame of science context (Thomas et al., 2008). Moreover, authors have stressed the greater efficacy of multi-method approaches that use a concurrent component in assessing metacognitive processes (Veenman, 2005). Following these suggestions, a recent report described the design and validation of a multi-method assessment of metacognition use in chemistry problem solving (Cooper, Sandi-Urena, & Stevens, 2008). This report specifically addresses the regulatory or skilfulness component of metacognition that comprises the skills generally described as planning, monitoring, and evaluating (Schraw et al., 2006). This multi-method assessment was the instrument chosen for this study; it has been described elsewhere (Cooper & Sandi-Urena, 2009; Cooper, Sandi-Urena, & Stevens, 2008) and therefore is only briefly presented in the next section. This paper describes and discusses the design of a collaborative intervention aimed at developing participants' awareness and use of regulatory metacognitive skills in the context of a university general chemistry laboratory course. The assessment of the effectiveness of the intervention utilizing a multi-method is discussed and plausible factors promoting metacognition use are proposed.

Multi-Method Assessment

The multi-method assessment combines two instruments: a prospective self-report, the Metacognitive Activities Inventory (MCAI) (Cooper & Sandi-Urena, 2009), and an online concurrent automated instrument, the Interactive Multimedia Exercises software (IMMEX) (Cooper, Cox, Nammouz, Case, & Stevens, 2008). The MCAI is a 27-item inventory that has been shown to be robust, reliable, and valid in assessing use of metacognitive skills when solving chemistry problems (Cooper & Sandi-Urena, 2009). Respondents select their agreement with the items from a 5-point Likert scale (1—strongly disagree to 5—strongly agree). The score is a percentage of the maximum number of points attainable, where a higher percentage corresponds to a higher self-reported use of metacognitive regulatory skills. The MCAI is administered using hard copies of the inventory and the participants enter their selections on an optical reader form. Typically, first-year college students take around 15 minutes to complete the inventory.

The IMMEX is a web-based platform that has been described in depth elsewhere (Cooper, Cox, Nammouz, & Stevens, 2007; Stevens, Johnson, & Soller, 2005; Stevens & Palacio-Cayetano, 2003; Underdahl, Palacio-Cayetano, & Stevens, 2001). It has been previously reported to provide insight into students' performance and problem-solving strategies (Cooper, Cox, et al., 2008). By using an HTML tracking feature, IMMEX creates a record of student's actions while problem-solving that are later modelled using artificial neural networks (ANN) and Hidden Markov Models. Once trained the system allows the rapid characterization of participants' problem-solving strategies by metacognitive level (Cooper, Sandi-Urena, & Stevens, 2008). For example, the characterization helps in determining which students may be guessing, failing to evaluate their processes, or randomly selecting items. This analysis leads to the use of three descriptors to identify metacognitive levels: high, intermediate, and low metacognition use. Several advantages of this concurrent assessment have been reported (Cooper, Cox, et al., 2008): high automation and time efficiency, minimal susceptibility to researcher's bias, and more naturalistic problem-solving setting.

The IMMEX performance data can also be modelled 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 cases are necessarily of the same difficulty level, a simple comparison of correctness might be misleading. Ability calculation factors in 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 and MCAI scores.

The IMMEX problem selected for use with the multi-method assessment of metacognitive activity, Hazmat, is based on inorganic qualitative analysis, has 38 different clones (unknown substances), and has been extensively studied (Case, Stevens, & Cooper, 2007; Cooper et al., 2007; Stevens et al., 2005). The prologue presents a scenario and offers no instructions beyond informing participants, they are to determine the identity of a spilled chemical. The problem space contains necessary background information or library items, such as a glossary, solubility tables, flame colour key, and so forth, as well as information specific to the individual unknowns such as flame test, precipitation and solubility tests, and physical properties. Upon selection of test items, a short animation is presented from which students can infer the result of the test. Students then consider their understanding and interpretation of results as they navigate the problem space. 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. Similarly, an efficient problem solver may not omit running a flame test, one of the most relevant pieces of information to solve this kind of problem. Students select those items from the problem space that they deem necessary to arrive at a solution and they have the option to constantly review their work. Feedback is available upon submitting answers to individual unknowns. Instructions for the IMMEX assignments are typically sent via email; students are given a full week to complete six cases, thereby allowing for stabilization of their strategy (initial attempts at the problem often result in exploration of the problem space and are not indicative of the problem-solving strategy on which the student eventually stabilizes). Support via email is offered over the assessment period.

Table 1 describes the parameters derived from using the multi-method assessment of metacognition use.

Intervention Design

The objective of the intervention was to provide an opportunity for students to engage in small group collaboration and individual work that promoted reflection

Table 1. Parameters obtained from the multi-method assessment

Parameter	Description	Representation	Source
Strategy	Metacognitive characterization of solution of qualitative inorganic unknowns.	States: high, H; intermediate, I; and low, L	Hazmat (IMMEX ANN and HMM modelling)
Ability	Maximum difficulty level of a case that a participant can probably solve.	20–80 range	Hazmat (IMMEX performance IRT modelling)
Solve rate	Ratio of cases solved correctly over total number of cases.	% Correct	Hazmat (IMMEX case correctness)
MCAI%	Self-reported use of metacognitive regulatory skills.	% Summative scale	Metacognitive activities inventory

about processes and products in a problem-solving situation. Listed below are the main considerations observed during the process of designing the intervention:

(1) We used a problem as the central focus of the activity since metacognition guides the problem-solving process at the same time that it improves its efficiency.
(2) The task promoted cognitive imbalance since we believed that this would engage students sufficiently so that they would work purposefully on the intervention. The shock of failure on an otherwise apparently simple task creates this disequilibrium and may awake students' curiosity and encourage them to ponder about the *why* and *how* of this occurrence.
(3) Researchers have collected evidence of metacognition development during collaborative work (Larkin, 2006) and through the practice of collective metacognitive activities (Case, Gunstone, & Lewis, 2001; Georghiades, 2006). Hausmann, Chi, and Roy (2004) have extensively studied the benefits that are associated with collaboration. Similarly, Sears and Schwartz (2007) found that students who were asked to "invent solutions to problems" (p. 18) in statistics were better prepared for future learning when collaborating in dyads than when working individually. As a consequence, the core of the protocol was designed as a collaborative 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. To facilitate group work, the intervention was embedded in a general chemistry laboratory course that is taught entirely in a cooperative format.
(4) To minimize the bias originating from instructors or researchers 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 instructors' expectations could influence the results.
(5) The intervention was named "Problem-Solving Activity" which is coherent with the context of the course and legitimizes its implementation as a laboratory assignment. However, the intervention was designed as a stand-alone activity, independent of the course and as such could be employed in a diverse array of learning environments. The activity does not address any chemistry-specific skills, but prompts the main aspects of regulatory skilfulness common to general problem-solving: planning, monitoring, and evaluating.
(6) The intervention was structured in three phases: A collaborative work session (Phase 1, about 45 minutes) followed by an individual component in the form of a take home assignment (Phase 2, about 20–30 minutes on-task time, collected a week later), and an individual feedback component (Phase 3, approximately 10 minutes, completed after turning in of Phase 2). Phase 3 is presented in the form of a summary; it explicitly states the objective of informing participants about the findings (most common errors, most common student opinions, and so forth). More detailed descriptions of the intervention components will be presented in later sections.

A review of the problem-solving literature identified problems that had been thoroughly studied and used in research and that could serve the purposes stated here. Three such problems were found (Davidson, Deuser, & Sternberg, 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 colour? (p. 218)[1]

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 12 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. (It must be mentioned here that this same problem has now been tested on multiple occasions with faculty, post-doctoral associates, and graduate students, and, in general, the findings by Davidson stated above have been supported.)

During Phase 1, dyads or triads of students were presented with the problem above and instructed not to continue with the next step of the activity until they had solved the initial problem. The strategy was to then present the correct answer for the problem (three is the minimum number of stockings necessary to make sure one has two of the same colour). The apparent obviousness of the answer and simplicity of the solution created an experience of cognitive imbalance that was used as a trigger for reflection. This engagement in reflection was then sustained by peer interaction and explicit metacognitive prompting. A series of prompts and questions followed, 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. Prompts were created and improved by a chemistry education research group of four individuals. The prompts were purposefully designed to be explicitly metacognitive (Davis, 2003), placing emphasis on the processes and not on the products of the problem-solving instantiation. Prompts were directive, meaning that they lead the participants to reflect about 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 complete one of the other two problems identified from the literature and were asked to address 13 prompts. Representative items used as prompts in both instances include:

- Do you think your group started working on the solution having a clear understanding of the problem? (yes) (no)
- Do you think that using a representation did improve/would have improved your performance? Explain briefly.

Phase 3 of the instrument presents participants with a summary of findings. In reality, the comments were produced from analyzing a few of the hundreds of interventions completed by students. The intention of this component is not to accurately inform the students about the study, but to reinforce awareness of metacognitive skills. 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. We hypothesized that these combined factors may facilitate internalization of learning and skills, and improve motivation. Table 2 shows an overview of the design of the intervention.

The collaborative metacognitive intervention was pilot-tested with a small group of General Chemistry 1 students prior to its use in the study. The main objectives of the pilot test were to verify intelligibility, to calibrate time of administration, and to fine-tune instructions. Observation during pilot-testing was crucial in confirming that the problem chosen fulfilled our expectations: students were challenged and shocked when they realized the problem was simple and the solution straightforward. Participants did spontaneously engage in team discussion; one tendency observed, which was certainly recurrent during the main study, was to extend the discussion to neighbouring 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 multi-method assessment: the MCAI and IMMEX (Hazmat) problem set (Cooper, Sandi-Urena, & Stevens, 2008). The study followed a quasi-experimental control and treatment group design with both instruments of

Table 2. Collaborative metacognitive intervention overview

Phase	Focus	Activities
Phase 1: Collective reflection	Promote reflection about metacognitive skilfulness 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 two or three participants
Phase 2: Individual reflection	Reinforce skills practiced during collaborative phase	One non-chemistry problem (chosen from two options) followed by 13 prompts. Assigned as homework, due one week later (Week 2), individual task
Phase 3: Feedback and summary of findings	Provide summary of findings compiled from students' responses, reflecting of activity as learning experience	General comments followed by eight prompts requiring responses. In lab, approximate duration 10 minutes, individual task

the multi-method used for the pre-test and the post-test 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 the General Chemistry 1 Laboratory course at a US south-eastern research university. Sections had a maximum enrolment of 24 students and were assigned to either conditions so that: (1) there were about the same number of sections from all three scheduling blocks (morning, noon, and afternoon) in the two conditions; (2) there was at least one section from each teaching assistant (TA) in each condition (typically TAs teach three laboratory sections); and (3) the initial number of students in the two conditions was similar (approximately 550 students in each condition). 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 were included in the study, and identification numbers were assigned to assure confidentiality. Neither the TAs nor the laboratory instructor who coordinates the TAs was 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 scripted instructions to their students 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.

Figure 1 shows the experimental design used for the treatment condition. "Lab session" refers to the weekly laboratory meetings. Lab sessions that were not relevant for the study design were left out of Figure 1. 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. Pretesting using the MCAI took place during the first week of laboratory instruction (Lab Session 1). The IMMEX assessment problem set, Hazmat, was assigned on the same day (Lab Session 1), and students were given a full week to complete six cases. Both conditions worked on their regular experimental project (Lab Sessions 1–4); during the beginning of the fifth weekly meeting (Lab Session 5), the treatment sections completed the collaborative component (Phase 1) of the Problem-Solving Exercise intervention. One week later (Lab Session 6), students in the treatment condition turned in the individual homework

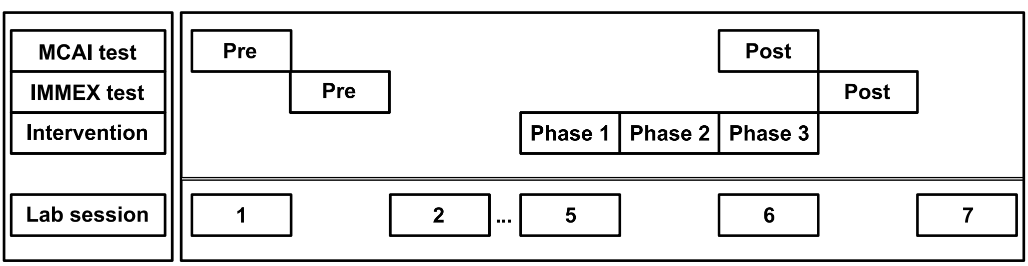

Figure 1. The experimental design used for the treatment condition

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; however, they completed the assignment after the data-gathering phase of the study. All students had previously been informed that due to limitations associated with the large enrolment of the course, not all sections would be performing the same tasks at the same time. Post-test of the MCAI was administered to all students, control and treatment conditions, during Lab Session 6. The same day, the IMMEX post-test was assigned and again participants had one full week to complete the assignment (due on or before Lab Session 7).

Participants in the treatment group who did not complete and turn in the individual component (Phase 2) were dropped from the study; the same applies to students who were absent during in-lab completion of Phases 1 and 3. This may account, at least in part, for a lower participant count in the treatment condition. Students with incomplete MCAIs or whose pre- and post-test administrations could not be matched were also dropped. Conflict with assessment for a parallel study precluded Hazmat IMMEX post-test of the entire treatment and control conditions. Alternatively, sections within each condition were randomly selected and led to about 200 students in each IMMEX group whose pre- and post-IMMEX assessments were matched.

Results

A chi-square association test for strategy distribution on the IMMEX problem Hazmat for the post-test showed no significant difference between the control and the treatment groups. In other words, student distribution amongst the high (H), intermediate (I), and low (L) metacognition user groups was not significantly different by condition. However, significant changes occurred for the self-reported use of metacognition, and Hazmat ability and solve rate. Table 3 shows the significant decrease in MCAI score for the treatment group while this parameter did not vary significantly for the control group. Calculation of Cohen's d comparing the post-test scores for the treatment and control conditions showed a "small" effect size (Cohen's $d = 0.1$).

Table 4 shows the pre- and post-test 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. According to Cohen's guidelines, the

Table 3. Effect of collaborative metacognitive intervention on self-reported metacognition use (paired sample t-test)

	MCAI%		
Group (n)	Pre-test	Post-test	p (paired samples)
Control (537)	76.0	75.3	.07
Treatment (464)	76.3	74.6	<.001

Table 4. Effect of collaborative metacognitive intervention on ability (paired sample *t*-test)

	Ability		
Group (*n*)	Pre-test	Post-test	*p* (paired samples)
Control (188)	51.2	51.8	.45
Treatment (159)	50.7	53.6	.003

Table 5. Effect of collaborative metacognitive intervention on solve rate (paired sample *t*-test)

	% Correct		
Group (performances)	Pre-test	Post-test	χ^2 (*p*- value)
Control (1124)	62.2	62.5	.03 (.86)
Treatment (956)	60.4	66.3	7.3 (.007)

effect size of the intervention on the ability was "small" (Cohen's $d = 0.2$). The post-test scores for the treatment and control conditions were used for the calculation of this parameter.

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). This parameter is calculated based on the number of performances (six per participant).

Discussion

This research contributes to the understanding of the effect of metacognitive instruction on metacognitive awareness and use. Assessment of the effect of the intervention on self-report use of metacognition indicated that the MCAI score decreased significantly for the treatment condition. Participants to whom the intervention was administered scored significantly lower in the MCAI post-test, while there was no significant change for the control group (Table 3). Initially, this decrease in the treatment group may seem counterintuitive 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 MCAI is a habitual behavior self-report and not an attitude inventory. In other words, what is being assessed is not the importance that participants place on the construct, but their habitual use of it. Therefore, raising the awareness about metacognition and increasing its perceived importance develops a more critical self-view and participants tend to self-rank more strictly, thereby lowering their scores. We propose that this behavior may be described as a consequence of a shift in the point of reference used when self-reporting and have obtained supporting evidence with other metacognition-enhancing interventions assessed with the same instrument (Sandi-Urena, Cooper, & Stevens, 2009). Typically, after being given the correct answer to the problem, students realized that they had engaged in solving the problem without reaching a clear understanding of the situation and had used superfluous information. This shocking effect was purposefully staged to engage participants in active reflection about their metacognition use; failure on an otherwise simple task is what we believe prompts the decrease in the MCAI post-test scores. When compared in terms of the effect size of the treatment, the two independent post-test groups showed a "small" difference, as indicated by Cohen's *d* value (0.1). There is little doubt about the advantages of quantifying differences between groups using effect size measures, as opposed to using statistical significance alone. However, caution must be exercised in interpreting effect size values since its practical importance needs to be judged in relation to other interventions seeking to have a similar effect, the nature of the outcome, and intervention characteristics such as duration, cost, and inherent ease of implementation (Glass, McGaw, & Smith, 1981). There is no reason to assume that criteria of practical significance for an intervention aimed at developing mastery of specific contents should be the same as those for one meant to act on individuals' intellectual skills. Coe (2002) maintains that very few educational interventions seem to have effects that would be described in Cohen's classification as anything other than "small". In education research, effect sizes as small as 0.1 may be considered of practical significance especially when the intervention implies small and inexpensive changes and the effect is cumulative over time. In the context of this study, we believe the practical significance of the intervention to be considerable since it achieves a positive effect on metacognitive awareness and ill-structured problem-solving ability (Cohen's $d = 0.2$) at a low cost and using little instruction time. Furthermore, the benefits from creating similar learning experiences may be cumulative. Nonetheless, calls for caution from other authors about the possibility of statistical significance being caused by statistical power (large N) should not be disregarded (Xitao, 2001).

After participating in the collaborative metacognitive intervention, students have a significantly increased ability to solve Hazmat problems (Table 4); that is, they can solve problems of higher difficulty. Solve rate results (Table 5) are consistent with this observation. Given that metacognition use has been described as a determinant factor in success solving ill-structured problems such as the one used for assessment here, we suggest that these results indicate that the intervention has indeed enhanced the use of metacognitive skills. This increase in actual deployment of metacognitive skills is paralleled by the increase in metacognitive awareness evidenced by the drop in MCAI scores discussed above. The convergence of these components of the multi-method in detecting the change induced by the intervention is entirely consistent with that previously reported for this assessment (Cooper, Sandi-Urena, & Stevens, 2008).

No significant change in strategy use was detected for either condition. Initially, we 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 post-test with the treatment group students using more metacognitive strategies. However, even though the treatment condition resulted in a small increase, it was not significant. In hindsight, reflection about the nature of the intervention may help explain such an outcome: retrospective reflection was stressed more than practicing of metacognitive skills. Apparently the cognitive imbalance posed by the realization that an otherwise simple task can be failed was the dominant factor during the activity. The MCAI is more useful to detect changes in awareness whereas the IMMEX is more appropriate to probe variations in problem-solving strategies. Subsequent studies have been designed and conducted to investigate the effect of prolonged practice of metacognitive skills in general chemistry laboratory environments (Sandi-Urena et al., submitted).

There are a number of questions that arise from these data. For example: How is the collaborative metacognitive intervention enhancing awareness of metacognition and enabling students to perform more metacognitively? What are the processes that underlie this effect? We would like to propose that the observed improvement is a consequence of two fundamental pillars that support the design of the intervention: prompting and collaborative interaction. An inspection of literature reveals several ways to classify prompts and even some discrepancies about what type of prompt has the best effects. 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). However, not all prompting is necessarily productive (Davis, 2003); therefore, careful interpretation must precede generalization of findings. Some of the characteristics of prompting and its use that should be considered are: the nature and intention of prompts, the thoughtfulness in the design of prompts, the methods of delivery, and the characteristics of the participants (for instance, autonomous learners may respond differently 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 (the solution is given before prompting starts), but to learn problem-solving skills from the exercise. This is what Davis (2003) called explicitly metacognitive prompts; the emphasis is placed on the process and not on the product of this particular problem-solving instance. However, it must be emphasized that participants are not taught how to solve problems or given a prescribed procedure they may memorize and use in future occurrences. The effect that prompts cue 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 of an increased awareness about metacognition, as evidenced by a drop in the MCAI score.

The second aspect regards the timing of the prompts. Typically, 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 tasks that for students' practical purposes were unrelated (completion of the MCAI and the IMMEX [Hazmat] problem set).

The second factor contributing to explaining the effectiveness of the intervention is its collaborative nature. Even though the prompts were formatted, delivered, and responded to in writing, reflection was not only evoked by the prompts themselves but also stimulated and magnified by the interaction with other students. Phases 2 and 3 were performed individually, but 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 on task performance. Previous reports regarding the effect of interventions (Case et al., 2007; Cooper, Cox, 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 et al. (2007) described gains in strategy and performance in solving the online problems for participants of a small collaborative group condition that had been instructed in the creation and use of concept maps. Another collaborative approach, Think Aloud Together, or TAT, engaged students in peer-prompting and was designed by 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 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 (taking the stance of a teacher or instructor), co-construction (elaboration or critical evaluation of peer's contributions), and self-directed explaining (listening to others' self-explaining). These mechanisms are not mutually exclusive, and in fact the intervention used in this study makes it possible for all three of them to take place alternatively during Phase 1. Particularly, the role of teacher facilitates developing competencies and confidence necessary to learn independently (Schwartz et al., 2005) and has proven to be significantly relevant for pre-formal thinking female students (Cooper, Cox, et al., 2008). As stated before, engagement in argumentation and discussion was observed to extend among different teams. The descriptions of the three mechanisms proposed by Hausmann et al. (2004) and their evidence 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.

Based on reported studies and the findings presented here, it is reasonable to suggest that the combination of appropriate prompting and collaborative work creates a learning environment conducive to the practice and enhancement of metacognitive skills. The results suggest that transfer of general metacognitive skills is possible at least over a short period of time. Enhanced achievement while prompting students during task performance (with automated computer generated support or instructor's support) does not provide evidence of students' ability to use the evoked skills independently. In this study, the prompts promote the practice of skills, but deployment of the learned skills occurs independently and in the absence of prompting.

Concluding Comments

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 multi-method assessment. The effectiveness of the intervention in enhancing metacognition use and awareness was successfully documented. The processes that underlie this enhancement are attributed to the combined effects of appropriate prompting and small group collaboration. Larkin (2006) suggested that "asking questions of oneself can begin by being questioned by others" (p. 23). In this study, 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 skills. We believe that these strategies can prepare students for future learning as students spontaneously adapt their knowledge to the new situation. The assessment employed is an adequate tool to measure this kind of knowledge (Schwartz et al., 2005). As described in the introduction, an overarching goal of education should be to enhance autonomous learning. The results presented suggest that this goal is achievable through learning environments such as the intervention used here.

This work makes two major contributions. First, it utilized a multi-method 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 for the claim that metacognitive skills developed during collaboration are transferable to the individual solution of an unrelated and independent task. Teachers can take advantage of the simplicity in implementation of prompting and collaboration and embed short activities during instruction. While the results reported here are from one instantiation of the intervention, if students were routinely exposed to such learning environments, one might hypothesize that even larger measurable improvements in many aspects of learning might result.

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Notes

1. The wording shown here is the same as originally used by Davidson et al. (1995). Students were instructed that in the context of the problem, "socks" and "stockings" were referred to the same object.

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