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Assessing Students' Use of Metacognition during Mathematical Problem Solving Using Smartpens

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Abstract: *This mixed methods study explored the pre and post use of metacognitive problem solving skills of 15 undergraduate students enrolled in a mathematics class in a Midwestern university. Participants' progress in their metacognitive self-talk and group-talk was monitored as they used Pulse® Smartpens to simultaneously capture their writing and spoken words that occurred during problem solving. Results of paired t-tests yielded statistically significant differences in participants' mean pre- and post-performance on the complete Metacognitive Awareness Inventory (MAI), and on regulation of cognition MAI items. Participants' self-talk and written solutions improved after gaining metacognitive awareness, yet apprehension about revealing cognitive inadequacies hampered capture of authentic self-talk.*
Keywords: *metacognition, self-talk, problem solving, knowledge of cognition, regulation of knowledge, think-aloud, Smartpens*

As students engage in mathematical problem solving they often use an initial problem-solving strategy, then—to various degrees—monitor their progress as the initial strategy is continued, or exchanged for new strategies until a viable solution is achieved (Cornoldi, Carretti, Drusi, & Tencati, 2015; Legg & Locker, Jr., 2009; Ponnusamy, 2009). Teachers typically ask students to review their problem-solving processes and reflect upon their work as they determine the reasonableness of their solution (Artz & Armour-Thomas, 1992; Pauli, Reusser, & Grob, 2007; Ponnusamy, 2009). This comprehensive process is closely tied to a concept known as metacognition, which may be formally defined as the process of sharpening the consciousness of one's knowledge or thinking while monitoring and reflecting upon that thinking (Aldhous, 2008; Dweck, 2014; Lee, Teo, & Bergin, 2009; Legg & Locker Jr., 2009; Lajoie, 2008; Pugalee, 2001; Schraw & Dennison, 1994; Steif, Lobue, Kara & Fay, 2010). Metacognition may also be referred to as an internal reflection process where individuals simultaneously monitor and regulate their thoughts while exercising control over their learning (Hacker, Dunlosky & Graesser, 2009; Ponnusamy, 2009).

Well-developed metacognitive skills support participants' thinking as they engage in problem solving while articulating the processes involved (Ponnusamy, 2009; Rompayom, Tambunchong, Wongyounoi, & Deschri, 2010). Teachers can better assist students in taking full advantage of metacognitive problem solving approaches when given some insight on their students' thought processes (Joseph, 2009; Ponnusamy, 2009). Although some students may have difficulty articulating their thought processes during a problem-solving episode; they may improve with practice and increased awareness of their metacognitive abilities (Hennessy, 2003; Pennequin, 2010).

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Metacognition is an important aspect in problem solving; however, effective means to enhance this skill in the classroom remain a challenge (Lee et al., 2009). To investigate internal metacognitive behaviors, self-talk or think-aloud protocols monitored by video- or audio-recordings have been used (Lajoie, 2008; Tajika, 2007; Van der Stel, 2008; Workman, 2004). Self-talk involves conscious or subconscious communication with oneself to understand what is required to solve a problem, and what next steps might be considered (Al-Hilawani, 2008; Güss, 2007; Pennequin, 2010; Wiezbicki-Stevens, 2009; Winsler, & Naglieri 2003). Schraw and Dennison (1994) investigated the conscious thought processes of students using think-aloud protocols and self-report inventories such as the Metacognition Awareness Inventory (MAI). Another metacognitive inventory supporting the use of metacognition to solve problems called for five basic steps: Careful Reading, Recall, Implement Possible Strategies, Monitor, and Evaluation (CRIME) (Montague & Applegate, 1993; Teong, 2003; Wong, 2007). These inventories, protocols, self-talk, and think-alouds may enhance metacognitive skills to support successful problem solving (Berthold, Nückles, & Renkl, 2007; Teong, 2003). However, attempts to quantify the findings from these studies have left many questions unanswered, with more recent studies employing mixed methods approaches to gain insight of this process (Bannert & Mengelkamp, 2008).

In earlier research studies investigating student thinking or problem solving abilities video cameras or tape-recorders were often used (as mentioned above). Participants may have felt self-conscious with video, and neither of those tools adequately captured what was being written at the time (or in-the-moment) (Grizzle-Martin, 2015; Johnson & Naresh, 2011; Lajoie, 2008; Teong, 2003; Workman, 2004). Studies using technology to understand metacognitive problem solving have seldom used tools that captured both verbal and written work simultaneously (Lajoie, 2008; Pauli et al., 2007). In this study, the Livescribe Pulse® Smartpen (hereafter simply referred to as a smartpen) is a computerized pen that captures both verbal and written work simultaneously (Freedman, 2010; McKeegan, 2008; Naone, 2008; Noel, 2008). Smartpen users may simply write with the pens without giving much thought of being monitored. Sharing their self-talk while writing their problem solving solutions may also give their teachers or tutors critical information needed to provide significant feedback to support improvement in problem-solving approaches as well as metacognitive thought (Freedman, 2010; Johnson & Naresh, 2011; McKeegan, 2008). The product of these captures of simultaneous writing and verbal sharing is referred to as a pencast. The pencasts are later available for uploads as pdf-documents, which with more recent technology, includes a play-back feature, which can be requested for any place in a written document merely by a click on the computer screen as the pencast is viewed. There is additional technology available (since this study was completed) to also support transcription to a chosen language. Given these related features, the efficient use of a smartpen may help to provide a reliable, relatively new source for data to use in the study of metacognition.

Background

Metacognition and its impact on problem solving has been studied across diverse fields, including mathematics, reading, and history (Kim, Park, Moore & Varma, 2013; Lee et al., 2014; Legg & Locker, 2009; Ponnusamy, 2009; Van der Stel, 2008). Metacognition is an essential skill for problem solving as students gauge their understanding of concepts to successfully solve problems (Güss, 2007; Lee et al., 2009; Capraro M., Capraro R., & Rupley, 2012). Pólya's four-step problem-solving model—(a) understand the problem; (b) devise a plan; (c) implement the plan, and (d) reflect on the reasonableness of the solution—is often cited as a basis for successful problem solving and consequently for fostering metacognitive skills (Al-Hilawani, 2008; Chamot et al., 1992). Other problem-solving heuristics have emphasized metacognitive problem solving (Arzt & Armour-Thomas, 2003; Pol, Harskamp, Suhre, & Goedhart, 2009; Pugalee, 2001; Steif, et al., 2010; Teong, 2003). The approach offered by Arzt and Armour-Thomas (2003) supports problem-solving steps using think-alouds, or self-talk.

The premise that students who engage in metacognitive behaviors are more successful than those who do not supports a suggestion that metacognitive behaviors should be taught and practiced to enhance participants' problem-solving abilities (Bannert, & Mengelkamp, 2008; Grizzle-Martin, 2015; Kramarski, & Friedman, 2014; Lee, 2014; Ponnusamy, 2009; Pugalee, 2001; Tajika, 2007; Teong, 2003).

Knowledge of cognition or meta-memory, represents the insight that learners possess of their memory systems and strategies for using them effectively (Legg & Locker, 2009). Three sub-processes facilitate these practices: (a) declarative knowledge; (b) procedural knowledge; and (c) conditional knowledge (Legg & Locker, 2009; Schraw & Dennison, 1994). These components have been extensively discussed in relation to problem solving (Chamot, Marsha, Michael, & George, 1992; Lee et al., 2009; Ponnusamy, 2009; Pugalee, 2001; Teong, 2003). Regulation of knowledge involves planning, monitoring and evaluation. It refers to learners' abilities to recognize their understanding of given information; identify and comprehend the basis of any flaws in logic; and select strategies to restore proper thinking when failures are identified (Chamot et al., 1992; Dweck, 2014). When presented with a problem, students need to first take time to understand it, then use their regulatory skills to fully understand what they are being asked to do before attempting solve it (Cornoldi et al., 2015; Hargrove & Nietfeld, 2015).

Learners who use metacognition efficiently are able to adjust their learning processes in response to their own perceptions of feedback about their learning experience (Cornoldi et al., 2015; Hargrove, & Nietfeld, 2015; Ponnusamy, 2009; Pugalee, 2001). Although some researchers disagree with the consideration of self-regulation as a feature of metacognition (Lajoie, 2008), others posit that self-regulation overlaps with conditional and procedural knowledge focusing on the capacity of learners to scrutinize their own learning, and to sustain the required attitudes to employ these strategies themselves (Fox, & Riconscente, 2008; Ponnusamy, 2009; Pugalee, 2001).

At times problem-solvers need external feedback such as communication from a teacher or tutor to foster the development of metacognitive problem solving skills (Al-Hilawani, 2008; Berthold et al., 2007; Cornoldi et al., 2015; Pennequin, 2010). The Mathematics Communication Standard (NCTM, 2000) highlights the importance of communicating in writing, especially for successful problem solving, and its role in supporting decisions regarding the use of metacognition (Burns, 1995; Pugalee, 2001; Steif, et al., 2010; Taylor, & McDonald, 2007). Through writing, students reflect on their learning, thought processes, and strategy choices while monitoring their problem-solving steps (Countryman, 1992; Pugalee, 2001; Taylor & McDonald, 2007). Nevertheless, many students are uncomfortable with writing detailed solutions, especially when they do not fully understand the concepts (Kim et al., 2013). As a result some metacognition researchers investigate external factors such as pedagogical approaches (Lee, 2014), while others investigate internal factors such as inner thoughts (Tajika, 2007).

Methodology

Research Design and Sample

This study investigated the metacognitive processes of undergraduate students engaged in mathematical problem-solving. The study took place in a Midwestern university with an enrollment of approximately 16,000 undergraduate and 2,000 graduate students. Potential participants were enrolled in an undergraduate mathematics class for middle childhood education majors, which emphasized problem-solving, technology, and the historical foundations for certain mathematics concepts. Of the 20 students (14 female and 6 male) enrolled in the class during the spring (2011) semester, 19 gave consent to participate in the study; however, only 15 participants subsequently completed the study. Most of the participants had taken a problem-solving mathematics course and Calculus I in previous semesters.

Research Questions

Four research questions guided this study:

1. Are the pre-assessment scores of participants' metacognitive awareness as determined by their performance on the Metacognitive Awareness Inventory (MAI) based upon the total MAI results, or the MAI sub-components of Knowledge of Cognition and Regulation of Cognition?

2. Are the post-assessment scores of participants' metacognitive awareness (as determined by their performance on the MAI) and their scores on the MCT positively correlated based upon the total MAI results, or the MAI sub-components of Knowledge of Cognition and Regulation of Cognition?

3. Does participants' metacognitive awareness as measured by the MAI improve after engaging in learning experiences in which they are asked to engage in metacognitive thinking?

4. Does participants' self-talk and writing of problem-solving solutions become more substantive after they improve their metacognitive awareness?

Instruments

This study used four instruments as described below.

Metacognitive Awareness Inventory (MAI). Participants completed the 52-item true/false MAI (Schraw, & Dennison, 1994) on the second day of class (see Table 1). The MAI assesses the two major components of metacognition: Knowledge of Cognition and Regulation of Cognition. Each item was assigned a 1-point score for participant's "true" response and 0 for "false." MAI scores were then determined based on the sum of points in each section. High scores on the MAI imply high levels of metacognitive ability.

Mathematics Content Test (MCT). The MCT, designed to assess students' knowledge of probability, was comprised of instructor-adapted content items from released national and international mathematics assessments (e.g., Third International Mathematics and Science Study (TIMSS); National Assessment of Educational Progress (NAEP); Program for

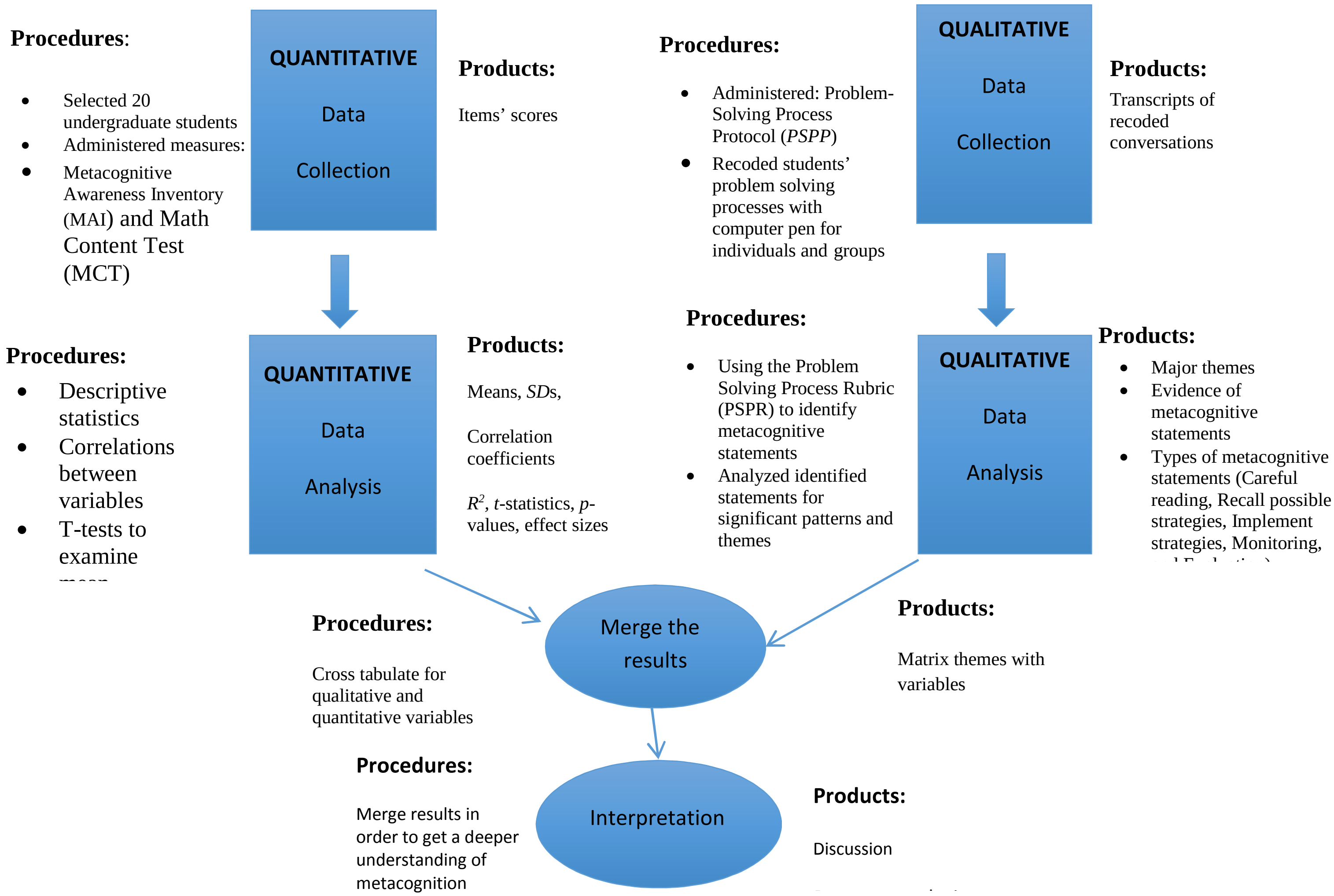

***Figure 1*:** Diagram representing a convergent design for this mixed-methods study adapted from Creswell, and Plano Clark (2011).

to the introductory lesson in the study; unfortunately, the post-MCT was not administered.

Problem-Solving Processes Protocol (PSPP). This instrument, designed to prompt students to use metacognitive strategies as they solve problems, was created using an adaptation of features found in two main sources: the problem-solving steps outlined in Pólya's Four-Step Model (Chamot, et al., 1992) and the CRIME strategy (Teong, 2003; Wong, 2007).

Problem-Solving Processes Rubric (PSPR). A five-category rubric designed to assess the participants' problem-solving actions while using the PSPP employed a 5-point Likert-type scale (0-4) to award points based on the researchers' assessment of the quality of participants'

Table 1
Items and Components of Metacognitive Awareness Inventory

Components of MAI	Subcomponents	Number of Items	Item Numbers
Knowledge about Cognition	Declarative	8	5, 10, 12, 16, 17, 20, 32, 46
	Procedural	4	3, 14, 27, 33
	Conditional	5	15, 18, 26, 29, 35
Regulation of Cognition	Information Management Systems	10	9, 13, 30, 31, 37, 39, 41, 43, 47, 48
	Debugging Strategies	5	25, 40, 44, 51, 52
	Planning	7	4, 6, 8, 22, 23, 42, 45
	Comprehension Monitoring	7	1, 2, 11, 21, 28, 34, 49
	Evaluation	6	7, 19, 24, 36, 38, 50

responses to PSPP prompts. Four points indicated clear portrayal of metacognitive behaviors in students' self-talk and written work, while 0 points indicated insignificant evidence of these behaviors (see Figure 2). The scores were crosschecked with the instructor-graded work for the class to reinforce reliability.

Problem-Solving Tasks. Problem-solving tasks were solved by the participants first as individuals, and later in groups of three or four students as assigned by the teacher. Students worked on the problems for two-week periods: Weeks 2, 4, 6, 8, and 12. Regular class instruction involved all students in the course in solving a problem solving task and recording the information verbally and in writing using the Smartpens.

Procedure

This study took place over a 12-week period in the spring semester in a computer laboratory where it was easy for participants to carry out the various assigned activities. The participants responded to the Pre-MAI survey and the MCT on the second day, after completing the informed consent letter. The Post-MAI was completed during the twelfth week of the semester. The course was designed such that the participants worked on problems individually (on their assigned Smartpens) before class, and during the first 15 minutes of class, before moving to their respective groups to complete their solutions. The group members shared their understanding of the problem and possible strategies to employ before they began work on their group solution. The groups (like the individuals) were required to record each step of the problem solving process on one smartpen and to upload the finished recording to the provided class e-mail at the end of class.

Student Name/Group: ______________________________________

CATEGORY	4	3	2	1	NS
Careful reading	Clear evidence of careful reading of question	Considerable evidence of careful reading of question	Some evidence of careful reading of question	Little or no evidence of careful reading of question	No evidence of careful reading of question
Recall possible strategy/ies	Participants clearly demonstrate recalling possible strategies for problem	Participants show considerable evidence of recalling possible strategies for solving the problem	Participants show some evidence of recalling possible strategies for solving the problem	Participants show little or no evidence of recalling possible strategies for solving the problem	Participants show no evidence of recalling possible strategies for solving the problem
Implement strategy/ies	Participants clearly define the strategy, and its correct implementation to begin solving the problem	Participants show considerable evidence in defining the strategy, and its correct implementation to begin solving the problem	Participants show some evidence of defining and correctly implementing the strategy to solve the problem	Participants show little or no evidence of defining and correctly implementing the strategy for solving the problem	Participants show no evidence of defining and correctly implementing the strategy for solving the problem
Monitoring	participants check on progress, question the approach, check/discuss whether a new approach/ strategy could be adopted	Participants considerably criticize approach with any one aspect of monitoring missing	Participants show some evidence of criticizing approach with any two aspects of monitoring missing	Participants show little or no evidence of criticizing problem solving strategy	Participants fail to criticize problem solving approach at all
Evaluation	After finding the solution, participants reflectively look back at the appropriateness of the strategy used, critically questioning its implementation and execution	There is considerable evidence of participants reflecting on strategy and its execution after solving the problem	There is some evidence that participants reflect on the strategy after solving the problem	There is little or no evidence of participants reflecting on the strategy after solving the problem	There is no evidence of participants reflecting on the strategy after solving the problem

Figure 2. Problem-Solving Processes Rubric (PSPR) used in qualitative analysis of pencasts adapted from the “Careful Reading, Recall, Implement Possible Strategies, Monitor, and Evaluation” (CRIME) (Teong, 2003).

Solutions of the first problem of the 12-week period were not supported by scaffolding from the PSPP to determine any initial student use of metacognitive processes. Subsequent problems were solved using the PSPP as a guide. The information collected via the Smartpens consisted of written information (i.e., pencasts) as participants solved problems, recorded self-talk of problem solving during individual work, and group-talk during collaborative work as participants returned to the work on the same problems together. Using the CRIME/PSPR rubric (Figure 2), the pencasts of nine randomly selected participants were analyzed. These pencasts, with real names removed, provided qualitative data that were transcribed and analyzed using a grounded theory approach to make note of patterns indicative of metacognitive thought as highlighted in CRIME and the metacognition literature. To gain additional insight on participants' metacognitive processes when working alone (self-talk) or in groups (group-talk) only group pencasts for which individual pencasts were also available were analyzed. For example, if Participant 12 (of Group A) was selected for the individual portion of a metacognitive self-talk analysis on the rock-paper-scissors problem, then Group A was selected for the group-talk analysis on that same problem.

Quantitative methods employing t-tests and Pearson Product Moment correlations were used to respond to the research questions involving the Pre- and Post-MAI and MCT data. Qualitative methods investigating patterns in responses and alignment of those patterns with metacognitive theory provided descriptions of the verbal and written data from the pencasts submitted via the Smartpens.

Results

The results of the quantitative strand for Questions 1 and 3 (highlighting comparison of means of metacognitive awareness (pre- and post-MAI) and mathematical content knowledge) are discussed followed by the qualitative results for Question 4 (highlighting self-talk and written problem solving responses.)

Question 1. Based upon the total preMAI results and the preMAI sub-components of metacognition (Knowledge of Cognition and Regulation of Cognition) the correlations were not statistically significant for the preMAI and the MCT $r = .226$, $p = .419$; and for the subcomponents of Knowledge ($r = .267$, $p = .336$) or Regulation ($r = .186$, $p = .507$).

Question 2. This question was not addressed since the post MCT was not administered due to circumstances beyond the researchers' control.

Question 3. Results of a paired t-test for the pre/post MAI showed a statistically significant difference in the mean performance of the participants, $t(14) = 3.620$, $p =. 003$, $d = .68$ before and after engaging in metacognitive activities over the period of the study. See table 2.

Table 2
Comparison of the Means of the Pre-MAI and Post-MAI

	M	*SD*	*t*
Pre-*MAI* (complete)	38.67	7.287	3.620**
Post-*MAI* (complete)	43.13	5.842	

**p < .01

Next the Next the mean differences for the subcomponents of knowledge and regulation on the pre- and post-MAI were evaluated through paired t-tests. Results for the pre and post regulation of cognition (MAI) items revealed a statistically significant difference in the mean performance of the participants $t(14) = 3.556$, $p =. 003$, $d = .68$ (see Table 3), while that for the pre and post knowledge of cognition (MAI) items did not.

Table 3
Comparison of the Means of the Regulation of Cognition (RC) Component of the Pre-MAI and Post-MAI

	M	*SD*	*t*
Pre-*MAI* (RC Component)	24.333	5.8757	3.556**
Post-*MAI* (RC Component)	28.000	4.8403	

$^{**}p < .01$

Question 4. Generally, there was improvement in the quality of participants' self-talk and writing of problem solving tasks when comparing the pre- and post-pencasts (as determined via the PSPR in Figure 1). However, participants applied metacognitive processes much better on tasks while in groups than as individuals in both the pre- and post-tasks. Overall, the participants exhibited less self-talk while problem solving than expected, somewhat in support of Vygotsky's (1978, 1986) suggestion that students tend to engage in self-talk more during early stages of learning, diminishing in this practice with age.

There was also meaningful change in the Careful Reading part of the PSPR (CRIME); however, participants provided little evidence to support analysis of how much time was taken to understand the problems before embarking on solution strategies. To further expand on the findings Table 4 highlights analysis for the following individuals and groups: Individual participants 1, 2, and 3 (denoted as I1, I2, I3) and Groups 1 and 2 (represented as G1, G2) regarding performance on the Rock-Paper-Scissors probability problem; and Individual 9 (I9) and Groups 3 and 4 (G3, G4) regarding performance on the Base 60 Fraction-Decimal Problem.

The numerals in Table 4 indicate the number of instances in which each of the CRIME components was found to occur in the pencasts. Although the optimal situation for analyzing the data for pre-/post-comparisons would include pencasts from the same groups (pre and post) and the same individuals (pre and post), the participation levels were not consistent throughout the study. The analysis that follows is designed to approximate what may be the reality of the CRIME metacognitive interactions in solving the two target problems.

Table 4
CRIME Rubric Ratings for Group and Individual Responses: Pre and Post

	Careful Reading	Recall possible strategy/ies	Implement strategy/ies	Monitoring	Evaluation
Rock-Paper-Scissor Problem (Early Metacognitive Experience)					
Group 1	**0**	**1**	**2**	**3**	**2**
Student 1	0	0	2	1	1
Student 2	0	1	2	2	1
Student 3	0	2	3	2	1
Group 2	**1**	**1**	**2**	**2**	**4**
Student 4	2	1	2	2	2
Student 5	1	1	2	1	1
Student 6	0	0	2	1	1
Fraction-Decimal (Base 60) Problem (Later Metacognitive Experience)					
Group 3	**2**	**1**	**3**	**3**	**4**
Group 4	**2**	**1**	**2**	**3**	**3**
Student 9	2	3	3	2	4

Discussion

Based on the quantitative results, the MAI and its components were not significantly related to the MCT which was designed with the intention of at capturing students' metacognitive practices while working on mathematics problems. While this result is expected at the beginning of the study given the participants' limited exposure to metacognitive practices, the small sample size (n = 15) could also be impacting the results. On the other hand, while it was not possible to examine the relationship between the post-MAI and the MCT, it is hoped that in this case the relationship would be statistically significant to validate participants' use of metacognitive practices when solving mathematics problems in paper. Comparison between the mean pre-MAI and the mean post-MAI showed that students' metacognitive awareness as measured by the MAI improved after they were engaged in metacognitive thinking learning experiences. This finding legitimizes the need to foster metacognitive practices among students during instruction. Finally, evaluating the growth in metacognition for the pre-and post- MAI subcomponents for knowledge and regulation of cognition revealed statistically significant differences only in the regulation component. The significant results for the regulation of knowledge component could indicate increased awareness by the end of the study. This finding is further supported by a relatively medium to large effect size despite the small sample size. Additionally, while there was not statistically significant difference in the pre- and post- component for the knowledge of cognition component, this result could be due to the weak statistical power due to the small sample size in the study. Evaluating the effect size for this component would provide additional details on growth in students' use of this MAI component.

Based on the qualitative findings, it appears that very little Careful Reading occurred for individual work. It was possible that participants were reading silently, not engaging in self-talk, or turning the audio off as they practiced their self-talk (as some participants later confessed) during individual sessions. This is a troubling situation considering the importance of careful reading for supporting metacognitive actions while problem solving (Capraro, Capraro, & Rupley, 2012). In comparing the participants' performance with the Rock-Paper-Scissors problem and the Fraction-Decimal (Base 60) problem, it appears that there were more instances of Careful Reading for the latter (Table 4). The participants might have been more familiar with the context of the Rock-Paper-Scissor problem, a commonly played game among students, and were more comfortable reading it out loud. However, the game is not commonly presented in a probability context to determine the chances of winning based upon the choices of three players in the game, it was thus difficult to speculate why self-talk or more substantive group-talk didn't suffice during problem-solving.

To provide more details about the performances that are summarized in Table 4, we return to the Rock-Paper-Scissors problem. Participants were asked to play the common game a few times in their groups before asking themselves (a) whether the game was fair; (b) whether each player had the same chance of winning on each turn; or (c) whether one selection (i.e., rock, paper, or scissors) gave a player a better chance of winning. Participants solved the Rock-Paper-Scissors problem prior to any specific training about use of metacognition in problem solving.

After participants experienced instruction in metacognitive processes—specifically in mathematical problem-solving—the Problem Solving Process Protocol (PSPP) was used as a guide. No Careful Reading was exhibited by the four individuals among participants selected for the analysis of the rock-paper-scissor problem, supporting the premise that novice problem solvers typically begin solving a problem without taking sufficient time to understand it (Jacobse & Harskamp, 2009). Little monitoring and reflection was evident in the pencasts. Two participants attempted to carefully read the problem before embarking on the problem-solving process. In this case both groups of participants performed fairly equally on the other categories of CRIME as seen in Table 4. Undetected factors may have led to this outcome, or participants might have neglected the Careful Reading having read the problem individually.

Limitations

Four limitations are identified for this study: (a) difficulty getting the participants to follow procedures such as proper labeling of their pencasts, submitting them in a timely manner, and authentically sharing their solutions to the problems; (b) difficulty getting the participants to sufficiently communicate in think-alouds or self-talk during problem solving; (c) inability to administer the post-assessment of the MCT due to circumstances beyond our control; and (d) technical pencast difficulties such as background noise of other deliberating groups, or participants speaking too softly.

Near the end of the qualitative analysis it became apparent that some participants solved the problems—without the pens at first—in a trial run. It is conjectured that important metacognitive thinking took place off-the-record! In other related research we discovered that similar situations occurred with high school students, other college mathematics students, and with classroom mathematics teachers who were taking graduate classes. Participants were assured that there should be no feelings of shame with regards to their mis-attempts or lack of knowledge, and that we were more interested in discovering how they approached problems and made corrective actions after thinking about their work. However, the participants felt uncomfortable with revealing any inadequacies as they attempted and sometimes struggled to solve the mathematical problems. It was difficult to complete some of the transcriptions adequately due to background noise during the group pencasts in class since there were times when sufficient physical space between the groups was not available. Moreover, while some participants were reluctant to capture their self-talk during the exercises and turned off the pens, others spoke in somewhat inaudible tones when they worked alone, still making it difficult to make sense of their thought processes. As a result the limited numbers of pencasts (shown in Table 4) were analyzed.

Implications for Future Practice and Conclusions

Direct instruction in use of metacognitive strategies, combined with approaches to support accountability for employing these strategies authentically, is necessary. One approach that warrants attention involves encouraging more consistent use of a protocol or checklist—both when solving problems individually and with a group. However, the fruits of this approach will be found when students use metacognitive strategies more habitually, without the use of the protocols or checklists. Whereas classroom teachers will not be able to listen to many pencasts on a regular basis for the level of desired analysis, significant insight may be gained by random selection of student work which may help to reveal errors in logic while problem-solving as well as areas to support improvement in metacognitive thought. Further research using smartpens to capture individual self-talk might also provide strategies for students to use what they hear from their own self-talk to build their own mental growth.

The work of Carol Dweck (Aldhous, 2008) regarding the establishment of a growth mindset may hold some promise for preparing students to engage in metacognitive thinking, while motivating themselves to freely solve problems while engaged in recorded self-talk unencumbered by fear of revealing their work-in-progress. Is it possible to pinpoint the sources of this fear in students' search for the correct answer, the correct way? Does this fear of sharing inner thinking, while solving problems, highlight a deeper emphasis on understanding problem-solving processes more than reinforcing the need to find the correct solution? Does the critical thinking called for in recent reform efforts in mathematics and other subjects support the use of more metacognitive thought and increased metacognitive awareness? Does the fear of failure with high-stakes assessments that seem to give more weight to final answers take away from the development of metacognitive thought?

Finally, these findings support the need for improvement in metacognitive practices as well as appreciation for the nature of mathematical problem-solving. Given a problem to solve there should be an expectation that there may be a lack of knowledge about exactly how to proceed to solve it, and hence an expectation for some trial-and-error as well as some missteps in finding a reasonable solution. More authentic sharing of in-the-moment thinking via self-talk, conveniently captured via the use of one of the many versions of smartpens, holds the potential for improved student performance with regards to the use of metacognitive thinking as well as more productive mathematical problem-solving, while also providing insight on these approaches to the classroom teacher.

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