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The Influence of Metacognitive Self-Regulation and Ability Levels on Problem Solving

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Abstract

Research states that metacognitive monitoring and control are important skills for successful problem solving (e.g., Artzt & Armour-Thomas 1992; Carr & Jessup, 1997; Hmelo & Cote, 1996; Tobias & Everson, 1995). In particular, research has demonstrated that certain self-regulatory and metacognitive skills predict problem solving success as well as or better than traditional predictors of general ability such as achievement scores (Swanson, 1990).

The purpose of this research study was twofold. First, we sought to examine particular metacognitive monitoring and regulatory skills in the context of solving science problems in a computer-based learning environment. Second we sought to confirm and extend Swanson's (1990) work using a different measure for metacognition and multiple measures of ability, achievement, and aptitude.

There were several noteworthy findings. Knowledge of Cognition, Objectivity, and Problem Representation predicted successful problem solving, as hypothesized. In terms of confirming and extending Swanson’s (1990) work, we found congruent results— high levels of metacognitive self-regulation compensated for low overall abilities. This research also confirmed Swanson's assertion that the constructs of metacognition and ability, achievement, and aptitude operate as independent processes. Results further demonstrated that metacognitive self-regulation was a better predictor of success at problem solving than many standardized measures used in classrooms across the country.

It is our hope that such research will eventually lead to the development of a model for problem-solving activities and computer-based materials that would foster metacognitive self-regulation.

Introduction

With the current emphasis in education on information management and the advent of the Internat as an educational resource, there is a great need for students to be able to self-regulate how they learn and acquire new skills. Research conducted over the last 15 years on self-regulated learning has primarily focused on three core components: metacognitive awareness, strategy use, and motivational control (Bruning, Schraw & Ronning, 1995). In the present study we focused on the influence of metacognitive awareness for effective use of problem solving strategies

There were two primary research goals. First, we examined five sub-components of metacognitive self-regulation as described by Howard, McGee, Shia, & Hong (2000) and their influence upon problem solving. The sub-components are:

- Knowledge of Cognition Measures how much learners understand about their unique cognitive abilities and the ways they learn best. Includes an awareness of one's own learning and memory processes as well as learning strengths and weaknesses.
- Objectivity Defined as standing outside oneself and thinking about one’s learning as it proceeds. Includes an awareness of one's learning goals and alternative choices in accomplishing a learning goal.
- Problem Representation Includes an awareness of strategies one uses to understand the problem fully before proceeding.
- Subtask Monitoring Defined as breaking the problem down into subtasks and monitoring the completion of each subtask.
- Evaluation Measures the degree to which students are aware of checking their work throughout the entire problem-solving process to evaluate if it is being done correctly.

Second, we sought to extend prior research in the area of metacognitive self-regulation and how it interacts with student ability, achievement, and aptitude in the context of solving problems. In 1990 H. Lee Swanson presented a pivotal work linking metacognition to successful problem solving. Swanson set out to demonstrate the independence of metacognition and general aptitude on various problem-solving measures. He defined aptitude as the propensity to successfully perform school-related tasks, and measured it using standardized, cognitive ability and achievement tests. He measured metacognitive ability using tape-

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recorded responses to a metacognitive questionnaire. His findings indicated that metacognition was more important for problem-solving success than aptitude and that in situations where students had low aptitudes but high metacognition, they performed as well as students who had high aptitude. Howard, McGee, Hong and Shia (2000) found results that coincided with Swanson's (1990) findings in the context of students learning through computer-based inquiry. Their research showed that those students with high metacognitive self-regulation compensated for low achievement on content understanding and problem solving measures. They used GPA as a measure of achievement. The ramifications of both of these studies are important given the strong emphasis educators have placed on ability indicators like aptitude and achievement by educators throughout the history of psychological measurement.

Hypotheses

1) All five sub-components of metacognitive self-regulation as measured by the Inventory of Metacognitive Self-Regulation (Howard, McGee, & Shia 1999) will predict success at problem solving.
2) High levels of metacognitive self-regulation will compensate for low overall achievement, ability, or aptitude.

In Swanson's (1990) work, he used two standardized measures to determine aptitude: the Cognitive Abilities Test (Thorndike & Hagen, 1978) and the Comprehensive Test of Basic Skills (1978). In Howard, McGee, Hong and Shia (2000), they used GPA as a measure of achievement. In the present study we sought to extend this research by using multiple measures of achievement, ability, and aptitude. Our subject pool was comprised of approximately fifteen hundred students in classrooms across the United States. In addition to collecting data on metacognitive self-regulation and problem solving outcomes, we asked teachers to also send any available data from student achievement, ability and aptitude scores already collected. A summary of the measures is presented in Table 1.

Table 1
Descriptions of Research Instruments and Number of Participants for Each

Test	Full Name and Version	N	Description
IMSR	Inventory of Metacognitive Self-Regulation	1536	Measures five metacognitive self-regulatory variables using a Likert-scale format: Knowledge of Cognition, Objectivity, Problem Representation, Subtask Monitoring and Evaluation. For ages 12-18.
-	Problem Solving measure	1502	Assesses problem solving skills such as drawing conclusions and making inferences. For grades 5-12.
			Achievement
-	Content Understanding	1420	Assessment of achievement within the present instructional context-- normalized across the subject population.
CTBS	Comprehensive Test of Basic Skills, Level C	29	Norm-referenced standardized achievement test. Subscales include: Language Arts, Mathematics, Science and Social Studies.
CTPIII	Comprehensive Testing Program III, Level E	126	Norm-referenced test for grades 6-8. Subscales include: Vocabulary, Reading Comprehension, Writing Mechanics, Writing Process, and Mathematics.
GPA	Grade Point Average	1184	Student grade point average, normalized across the subject population.
SAT 9	Stanford Achievement Test- 9th Edition, S Form, Intermediate Level	228	Criterion-referenced standardized achievement test. Subscales include: Reading, Math, Language, and Science.
			Science Achievement
ITBS	Iowa Test of Basic Skills- Science Performance Assessment, Grades 8 & 9	57	Norm-referenced constructed-response test which assesses strategic thinking and problem solving capabilities in the domain of science.
MEAP	Michigan Educational Assessment Program- Science Subscale	164	Criterion-referenced test which measures what students know and what students are able to do. Given in grades 5 and 8.
EOT	Seventh Grade Science Essential Outcomes Test	124	Criterion-referenced test given in 7th grade. Developed by the Rochester, NY School District to measure science achievement.
			Cognitive Ability
Cornell	Cornell Critical Thinking Measure, 3rd Edition, Level X	44	Measures specific critical thinking abilities: Induction, Credibility, Deduction, and Identification of Assumptions. For grades 5 through college-level.
MAT	Matrix Analogies Test, Short Form	40	Measures nonverbal reasoning ability. For ages 5-17.
TER	Test of Everyday Reasoning	46	Measures critical thinking judgements made in everyday situations. For grades 6 and up.
			Aptitude
OLSAT	Otis-Lennon School Ability Test, 7th Edition, Level E	48	Measures cognitive reasoning skills which relate to a student's ability to learn and succeed in school. Level E is for students in grades 4 and 5.

Note. All the instruments described here use multiple-choice questions, unless stated otherwise.

Method

Participants

Participants included 1502 students, grades 5–9, from schools across the United States. They represented a cross-section of socioeconomic backgrounds and urban/suburban/rural categorizations. The ethnic breakdown included 36.5% Caucasian, 4.7% Asian American, 2.3% African American, 1.3% Hispanic or Latino, and 55.2% other or not reported. By gender, the breakdown was 45.7% female, 47.6% male and 6.7% not reported.

Procedure and Materials

Learning Outcomes

Students used Astronomy Village® Investigating the Solar System™ software for approximately 20 instructional days (see McGee & Howard, 1999 for a description of Astronomy Village®). Students were assessed on two learning outcomes: Content Understanding, and Problem Solving. The Content Understanding measure focused on the core requirements for life and planetary processes as presented in the software. In the present study Content Understanding was used as an independent variable representing achievement within this particular learning context. The Problem Solving measure focused on drawing conclusions from data and making inferences about planetary processes. The instrument was validated as part of the Astronomy Village development project sponsored by the National Science Foundation (McGee, Howard, Dimitrov, Hong, & Shia, 2001)

Inventory of Metacognitive Self-Regulation

At pretest time, students took the Inventory of Metacognitive Self-Regulation (IMSR) which measures five factors related to awareness of learning processes and control of learning strategies: (1) Knowledge of Cognition, (2) Objectivity (3) Problem Representation, (4) Subtask Monitoring, and (5) Evaluation (Howard, McGee & Shia, 1999). The IMSR includes 32 items that use a five-point Likert scale. For each of the 32 items, students are instructed to circle the answer that best described the way they solve problems in math or science class (1=never, 2=seldom/rarely, 3=sometimes, 4=often/frequently, 5=always). The validation of the IMSR is discussed elsewhere (Howard, McGee, Shia, & Hong, 2000).

Achievement, Cognitive Ability, and Aptitude Measures

We collected achievement, cognitive ability, and aptitude scores from classroom subsets of the total 1502 students according to Table 1. Achievement indicators included both norm-referenced and criterion-referenced standardized tests including the Comprehensive Test of Basic Skills, Comprehensive Testing Program III, and Stanford Achievement Test. We placed student grade point average and the Content Understanding measure in the achievement category as well. Three of the tests in this category measured achievement specifically in the area of science (Iowa Test of Basic Skills, Michigan Educational Assessment Program, and the Seventh Grade Essential Outcome Test). Cognitive ability measures included the Cornell Critical Thinking Measure, the Matrix Analogies Test, and the Test of Everyday Reasoning. The Otis-Lennon School Ability Test measures aptitude and cognitive reasoning skills which relate to a student's ability to learn and succeed in school. Achievement and aptitude measures are presented in national percentile scores. A description of each inventory is provided in Table 1 as well. For ease of discussion, we will collectively call these instruments "ability" measures.

Results

For all analyses, we used the general linear model (GLM), which is a unifying analysis technique that includes both analysis of variance and multiple linear regression. When the analysis involved examining differences, ANOVA results are reported. When the analysis involved examining relationships, multiple regression results are reported.

Initial analyses revealed that both gender and age were significant predictors of a student's overall metacognitive self-regulation score ($ß = -.137$, $p \leq 0.0001$, and $ß = .061$, $p \leq 0.0001$, respectively). In this case, females had significantly higher Total IMSR scores. In all subsequent analyses, variability due to age and gender was removed.

Our first hypothesis was that each of the five sub-components of metacognitive self-regulation would predict success at problem solving. Overall, the IMSR total score was a significant predictor of Problem Solving, $ß = .149$, $p \leq 0.0001$. See Table 2 for more details. In addition, three of the five factors (Knowledge of Cognition, Objectivity, & Problem Representation) were also significant predictors ($ß = .082$, $p = .0217$, $ß = -.071$, $p = .0402$, and $ß = .115$, $p = .0021$, respectively).

Table 2

Summary of Multiple Regression Analysis: IMSR Total and Subscales as Predictors of Success at Problem Solving (N=1417)

Variable	Coefficient	SE	T ratio	p value
IMSR	.25	.04	5.55	≤ .0001*
Knowledge of Cognition	.63	.28	2.30	.022*
Objectivity	-.46	.22	-2.05	.040*
Problem Recognition	.77	.25	3.09	.002*
Subtask Monitoring	.30	.27	1.10	.270
Evaluation	.08	.23	0.35	.724

Note. IMSR = Inventory of Metacognitive Self-Regulation
*$p < .05$.

Our second hypothesis was that high levels of metacognitive self-regulation would compensate for low overall achievement, ability, or aptitude. Swanson (1990) conducted 2 X 2 ANOVAs, categorizing students according to metacognitive ability and aptitude (High v. Low Metacognition X High v. Low Aptitude). His results revealed an interaction between the High Metacognition/Low Aptitude group and the Low Metacognition/High Aptitude group. In order to test for similar interactions, we also used 2 X 2 ANOVAs— one for each of the twelve instruments. According to our hypothesis, one would expect a significant interaction between these two groups, with the High Metacognition/Low Ability group outperforming the Low Metacognition/High Ability group.

In order to group students into High and Low Metacognitive Self-Regulation and High and Low Ability, we used mean scores as the cutoff. In the case of student GPA, we had a large enough subject pool that we used the top and bottom 27^{th} percentiles.

Mean scores on Problem Solving for each cell in the 2 X 2 are presented in Table 3 for each instrument. The interaction statistics between the two cells of interest are also shown. Using $\alpha = .004$ to account for the Type I error rate due to numerous analyses, six of twelve instruments showed significant interactions between the cells of interest. These six included Content Understanding, the CTP III, the SAT 9, the EOT, the TER and the OLSAT. These six span all three categories of achievement, cognitive ability, and aptitude. It should be noted that with the exception of the MEAP, the High Metacognition/Low Ability group had higher mean scores than the Low Metacognition/High Ability group in every instance. This is illustrated in Figure 1.

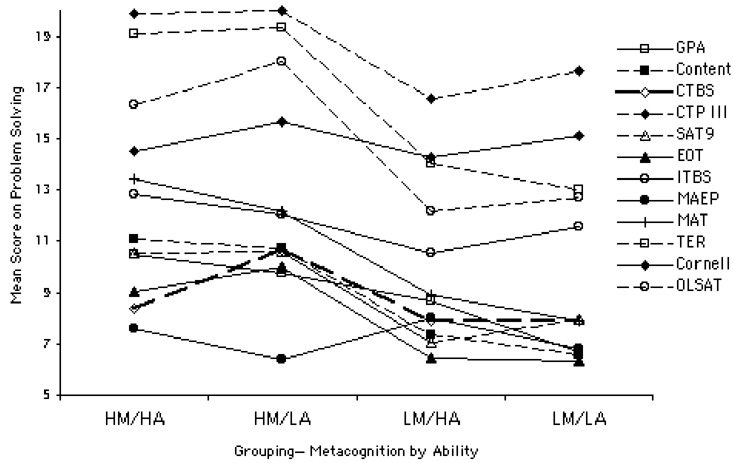
Table 3
Summary of Mean Scores on Problem Solving as a Function of High and Low Metacognition and High and Low Ability, with Selected Interaction Statistics

Test	HM/HA	HM/LA	LM/HA	LM/LA	Scheffe Post Hoc Tests for Interaction (HM/LA Compared to LM/HA) SE	p value
			Achievement			
Content	11.08	10.74	7.38	6.56	0.36	≤ 0.0001*
CTBS	8.34	10.68	7.91	7.89	1.16	0.021
CTP III	19.89	19.98	16.57	17.67	0.85	0.0001*
GPA	10.49	9.75	8.68	6.71	0.83	0.195
SAT9	10.56	10.62	7.08	7.97	0.57	≤ 0.0001*
			Science Achievement			
ITBS	12.81	12.05	10.53	11.58	2.01	0.455
MEAP	7.58	6.36	8.03	6.80	0.80	0.039
EOT	9.03	10.00	6.47	6.35	0.78	≤ 0.0001*
			Cognitive Ability			
Cornell	14.54	15.65	14.28	15.12	2.38	0.568
MAT	13.44	12.17	8.89	7.90	1.58	0.045
TER	19.07	19.33	14.04	13.00	1.65	0.003*
			Aptitude			
OLSAT	16.30	18.00	12.15	12.70	1.89	0.003*

Note. HM = High Metacognition; LM = Low Metacognition; HA = High Ability; LA = Low Ability.

*$p < .004$.

Figure 1. Mean score on problem solving as a function grouping and instrument



Discussion

The Five Sub-Components of Metacognitive Self- Regulation

The fact that three of the five metacognitive self-regulation sub-components (Knowledge of Cognition, Objectivity, & Problem Representation) were important for problem solving has considerable implications for theory related to self-regulated learning. First, the results indicate that Knowledge of Cognition is important for problem solving. To our knowledge, this is the first empirical study to report this connection. It is unclear in the research whether the acquisition and use of problem solving strategies necessarily depends on one's knowledge about or awareness of their cognition. Although many assume the mindful use of regulatory processes may precede effective use of problem solving strategies, this may not be the case. For example, consider the situation where problem solving strategies have become automatized (Sternberg, 1986). Awareness of one's learning processes may not be necessary for effective learning (Brown, 1987; Hacker, 1998; Kanfer & Ackerman, 1989).

Second, the research indicates that Objectivity and Problem Representation are important predictors for successful problem solving. Objectivity— the notion of standing outside oneself and thinking about one's learning— is often discussed as an important goal of interventions which teach learning strategies. Is one's objectivity an innate ability or is it a skill to be taught? Clearly more research into this sub-component of metacognitive self-regulation is warranted. Many researchers have described and studied the process of problem representation (e.g., Bransford & Stein, 1984; Ellis & Siegler, 1994; Hayes, 1978; Hunt, 1994; Reimann & Chi, 1989; Sternberg, 1986). In fact, Jonassen (2000) stated that problem representation is the most critical element for problem solving. The Problem Representation sub-component, as defined by Howard and colleagues (2000), measures the degree to which one is aware of strategies they use to understand a given problem. If becoming aware of the need to understand a problem before proceeding is important for successful problem solving, perhaps future research should investigate methods by which this awareness can be taught or at least supported through the instructional materials.

The fact that Subtask Monitoring and Evaluation were not predictors of problem solving is understandable in retrospect. Monitoring and evaluation tasks may not have been necessary for success at problem solving because the problems presented were of a short-term nature. On the assessment, the learner only needed to read a scenario and apply problem solving skills in one instance to solve the problem and then move on. Monitoring and evaluation would not be needed under these conditions to do well.

So what do the results mean for the design of instruction? There are two directions that emerge. First, if Knowledge of Cognition, Objectivity, and Problem Representation are important precursors to successful problem solving, instruction should be tailored to foster these skills. Since some believe that metacognitive abilities are innate and therefore slow to change, how to do this would be a research question of capital importance. White and Fredriksen (1998) and Davis (1996; 1998; 1999) made in-roads in this area which demonstrated how to promote the development of metacognitive skills through well-placed prompts and journaling activities. One implication from such research is that if it is possible to train students in utilizing metacognitive strategies, this training can help students to succeed in spite of low ability levels, achievement, or aptitude. Second, it may behoove instructional designers to consider how to develop problem solving activities to compensate for students' metacognitive weaknesses. For example, a student who is unaware of their cognitive strengths and limitations as they pertain to the task at hand, could be prompted to complete a worksheet, or have a discussion with their peers about choosing learning strategies before proceeding.

Metacognitive Self-Regulation v. Ability

Swanson's research has been heralded as a crucial turning point for research in metacognition and problem solving. The research reported here provides an important confirmation of Swanson's findings and extends it into two new areas. In terms of confirming Swanson's (1990) work, we found congruent results: high levels of metacognitive self-regulation compensated for low overall abilities. In addition, our research confirmed Swanson's assertion that the constructs of metacognition and ability, achievement, and aptitude operate as independent processes. Furthermore, the results lend additional construct validity to the self-report measure of metacognitive self-regulation, the IMSR (Howard, McGee, & Shia, 1999).

In terms of extending Swanson's (1990) work, we found that Knowledge of Cognition, Objectivity, and Problem Representation were important self-regulatory variables for effective problem solving. We also found that the results withstood the scrutiny of using various measures of ability, achievement, and aptitude. Six of twelve measures showed a significant interaction between High Metacognition/ Low Ability and Low Metacognition/ High Ability groups. The results demonstrated that metacognitive self-regulation was a better predictor of success at problem solving than these standardized measures used in classrooms across the country.

As shown by the results, students with high abilities may not need to utilize metacognitive self-regulation as much as those of lesser ability. This idea is consistent with prior research which found metacognition to be unimportant for familiar learning environments (Schwartz, Andersen, Howard, Hong & McGee, 1998).

References

Artzt, A. F., & Armour-Thomas, E. (1992). Development of a cognitive-metacognitive framework for protocol analysis of mathematical problem solving in small groups. Cognition and Instruction, 9, 137-175.

Bransford, J. D., & Stein, B. S. (1984). The ideal problem solver. San Francisco: Freeman.

Brown, A. (1987). Metacognition, executive control, self- regulation, and other more mysterious mechanisms. In F. E. Weinert & R. H. Kluwe (Eds.), Metacognition, motivation, and understanding (pp. 65-116). Hillsdale, NJ: Lawrence Erlbaum Associates.

Bruning, R. H., Schraw, G. J., & Ronning, R. R. (1995). Cognitive psychology and instruction. Englewood Cliffs, NJ: Merril.

Carr, M., & Jessup, D. L. (1997). Gender differences in first-grade mathematics strategy mathematics strategy use: Social and metacognitive influences. Journal of Educational Psychology, 89(2), 318-328.

CTB Macmillan/McGraw-Hill. (1978/1990). Comprehensive test of basic skills: Science subscale (4th ed.). New York: CTB Macmillan/McGraw-Hill.

Davis, E. A. (1996). Metacognitive scaffolding to foster scientific explanations. Paper presented at the annual meeting of the American Educational Research Association, New York.

Davis, E. A. (1998). Reflection prompts in the knowledge integration environment. Paper presented at the annual meeting of the American Educational Research Association, San Diego, CA.

Educational Testing Service. (1993). Comprehensive testing program III. Princeton, NJ: Educational Testing Service.

Ellis, S., & Siegler, R. S. (1994). Development of problem solving. In R. J. Sternberg (Ed.), Thinking and problem solving (pp. 333-368). New York: Academic Press.

Hacker, D. J. (1998). Definitions and empirical foundations. In D. J. Hacker, J. Dunlosky, & A. C. Graesser (Eds.), Metacognition in theory and practice (pp. 1-23). Mahwah, NJ: Lawrence Erlbaum Associates.

Harcourt Brace Educational Measurement. (1996). Otis-Lennon school ability test (7th ed.). San Antonio, TX: Psychological Corporation.

Harcourt Brace Educational Measurement. (1996). Stanford achievement test (9th ed.). San Antonio, TX: Psychological Corporation.

Hayes, J. R. (1978). Cognitive psychology: Thinking and creating. Homewood, IL: Dorsey.

Hmelo, C. E., & Cote, N. C. (1996). The development of self-directed learning strategies in problem-based learning. Paper presented at the Proceedings of the International Conference of the Learning Sciences, Evansdale, IL.

Howard, B. C., McGee, S., Hong, N., & Shia, R. (2000). The influence of metacognitive self-regulation on problem solving in computer-based science inquiry. Paper presented at the annual meeting of the American Educational Research Association, New Orleans, LA.

Howard, B. C., McGee, S., Shia, R., & Hong, N. (2000). Metacognitive self-regulation and problem solving: Expanding the theory base through factor analysis. Paper presented at the annual meeting of the American Educational Research Association, New Orleans, LA.

Hunt, E. (1994). Problem solving. In R. J. Sternberg (Ed.), Thinking and problem solving (pp. 215-231). New York: Academic Press.

Jonassen, D. H. (2000). Toward a design theory of problem solving. Educational Technology Research and Design, 48(4), 63.

Kanfer, R., & Ackerman, P. L. (1989). Motivation and cognitive abilities: An integrative/aptitude-treatment approach to skill acquisition. Journal of Applied Psychology, 74, 657-690.

McGee, S., & Howard, B. (1999). Generalizing activity structures from high school to middle school science. In S. McGee (Chair), Changing the game: Activity structures for science education reform. Symposium presented at the annual meeting of the American Educational Research Association, Montreal, Canada.

McGee, S., Howard, B. C., Dimitrov, D. M., Hong, N. S., & Shia, R. (2001). Addressing the complexities of evaluating interdisciplinary multimedia learning environments. Paper presented at the annual meeting of the American Educational Research Association, Seattle, WA.

Michigan State Board of Education. (1999). Michigan educational assessment program: Science subscale. Lansing, MI: Michigan State Board of Education.

Psychological Assessment Resources. (2001). Matrix analogies test, short form. Odessa, FL: Psychological Assessment Resources, Inc.

Reimann, P., & Chi, M. T. H. (1989). Human expertise. In K. H. Gilhooly (Ed.), Human and machine problem solving (pp. 161-191). New York: Plenum Press.

Riverside Publishing. (2000). Iowa test of basic skills: Science performance assessment. Itasca, IL: Riverside Publishing.

Rochester Independent School District. (1996). Seventh Grade Science Essential Outcome Test. Rochester, NY: Rochester Independent School District.

Schwartz, N., Andersen, C., Howard, B. C., Hong, N., & McGee, S. M. (1998). The influence of configurational knowledge on children's problem-solving performance in a hypermedia environment. Paper presented at the annual meeting of the American Educational Research Association, San Diego, CA.

Sternberg, R. J. (1986). Intelligence applied: Understanding and increasing your intellectual skills. San Diego, CA: Harcourt Brace Jovanovich.

Swanson, H. L. (1990). Influence of metacognitive knowledge and aptitude on problem solving. Journal of Educational Psychology, 82(2), 306-314.

Thorndike, R., & Hagen, E. (1978). Cognitive abilities test. New York: Houghton Mifflin.

Tobias, S., & Everson, H. T. (1995). Development and validation of an objectively scored measure of metacognition appropriate for group administration. Paper presented at the annual meeting of the American Educational Research Association, San Francisco.

White, B., & Frederiksen, J. (1998). Inquiry, modeling, and metacognition: Making science accessible to all students. Cognition and Instruction, 16(1), 3-118.

Zimmerman, B. J. (1989). Models of self-regulated learning and academic achievement. In B. J. Zimmerman & D. A. Schunk (Eds.), Self-regulated learning and academic achievement (pp. 1-25). New York: Springer-Verlag.