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Metacognition as means to increase the effectiveness of inquiry-based science education

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Abstract

The Teaching Science as Inquiry (TSI) philosophy is based on the belief that science should be taught and learned as it is practiced within the discipline of science education. TSI pedagogy uses a defined theoretical framework to counter the many vague misconceptions about inquiry. This framework a) acknowledges the multiple stages through which scientists progress within scientific inquiry, b) recognizes the many ways in which scientists seek new knowledge, and c) proposes that students and teachers mirror these phases and modes of inquiry. Two year-long professional development (PD) courses built on the TSI framework and grounded in the context of aquatic science have incorporated explicit teaching of metacognitive strategies as a way to access the process and learning of science. Preliminary findings from these PD courses suggest that explicit instruction in metacognitive strategies to teachers (N = 28) and their students (N = 648) has increased the ability of both groups to become more aware of their observations, decisions, and thought processes needed to do and understand science. The metacognitive strategies provided teachers with concrete actions and thought processes to reflect upon. TSI provided the language to allow teachers and students to discuss, and ultimately assess, their metacognitive growth. We feel that metacognitive reflection coupled with disciplinary inquiry has the potential to effect change in the teaching of scientific process and scientific thought, with the result that students become better critical thinkers and more scientifically literate. In this paper, we share the metacognitive methodologies we have developed, present findings from our PD courses, and provide suggestions for future research.

Key words: *professional development, learning cycle, science education, TSI*

Introduction

Inquiry-based science teaching has, at its foundation, the goal of producing students who are scientifically literate. In our view, one of the most important elements of scientific literacy is

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recognizing and participating in science as a discipline. According to King and Brownell (1966), a discipline of knowledge shares a common set of characteristics within a community of persons. These characteristics of a discipline include a tradition of practice, a conceptual structure, a specialized language, a set of beliefs, and a network of communications. Science as a discipline has a unique, systematic process of knowledge generation used to inquire about the natural world. Scientifically literate students understand that science is not only a body of facts, but also a dynamic, knowledge-creation process involving scientific habits of mind such as critical analysis, curiosity, openness to new ideas, and inventiveness (see National Research Council, 1996). This disciplinary view of science is, unfortunately, in direct contradiction to the way that science is typically taught and assessed, which contributes to students' misconception that science is just a collection of facts (Smith, Maclin, Houghton, & Hennessey, 2000; Smith & Wenk, 2006).

Misconceptions about the scientific process are due in part to the misrepresentation of the discipline of science by teachers, whose understanding of science often does not include mastery of the scientific habits of mind considered necessary by science experts (see Zembal-Saul, Munford, Crawford, Friedrichsen, & Land, 2002). This lack of preparation is not the fault of teachers; in the traditional teaching and learning of science, direct experience and confrontation of fixed epistemic beliefs often does not occur until the professional level, when scientists are at the forefront of knowledge extension. It is not until this point that many scientists fully understand how complex and uncertain knowledge is, how uncertain experts are, how much experts disagree, and how normal this uncertainty is (Carey & Smith, 1993). Therefore, teaching of scientific process skills can be especially difficult for secondary science teachers who lack experience conducting authentic scientific research (see Wee, Shephardson, Fast, & Harbor, 2007). Because the incorporation of inquiry-based scientific practices and multidirectional knowledge construction in teaching is a complex endeavor that requires significant effort, practice, and attention, even teachers with adequate experience practicing scientific habits of mind in the context of science research can struggle to include scientific practices into their classroom teaching (see Hammer, 1999). For these reasons, secondary science teachers often adhere closely to the linear scientific method espoused in many science textbooks (i.e. question, hypothesis, experiment, results, conclusion). As a result, teachers tend to perpetuate the epistemic belief that scientific knowledge is generated in a single, fixed manner. Students, in turn, tend to believe that scientific knowledge is "fixed, unchanging, absolute truth" rather than a "dynamic entity that will continue to evolve over time" (Ormrod, 2011). Correspondingly, students think the process of doing science is "memorizing procedures and formulas" to find a "single right answer" (Ormrod, 2011). The end result is that students continue to struggle to navigate the scientific process effectively.

We believe that becoming more aware of their thinking will help both teachers and students to understand the complex nature of the scientific process and participate in the discipline of science. To effect this change, we have introduced metacognitive strategies in our teacher professional development (PD) courses as a way to help teachers bridge inquiry and pedagogy in the implementation of curriculum and content in the classroom. Our PD is grounded in the Teaching Science as Inquiry (TSI) pedagogical framework, which is centered on learning through authentic application of knowledge and skills, where students learn science by doing science as authentically as possible (Seraphin, & Baumgartner, 2010).

The TSI framework is designed to help teachers teach not only basic scientific concepts, but also the multidirectional process used to understand and refine those concepts over time. In TSI PD, teachers are taught to help students evaluate and decide which inquiry techniques to use during their investigations. To increase the effectiveness of the TSI framework, we are investigating the scaffolding of metacognitive strategies over the course of the PD, beginning with explicit discussions of metacognition and building towards automatic, internalized practice of metacognition in both teachers and students. We argue that metacognition facilitates the process of teaching and learning science in a multidirectional, authentic way because it encourages students to become aware of their thinking process and mirror the behaviors of professional scientists.

Theoretical background: the role of metacognition in learning

Metacognition is often interpreted as "thinking about your thinking" and involves both awareness and control of one's cognitive processes. The National Research Council (2001, p. 78) defines metacognition as "the process of reflecting on and directing one's own thinking". Application of metacognitive skills requires knowledge of learning strategies and an awareness of when to appropriately apply each strategy (Schraw, Crippen, & Hartley, 2006). In addition to this awareness, or knowledge component, there is a control, or regulation component (Flavell, 1976; Brown, 1987), which involves evaluating what you currently know and determining what you still need to learn. For learners, metacognition is a complex process that entails assessing the task at hand, evaluating knowledge and skills, planning an approach, applying various learning strategies, and reflecting on the approach, with adjustment as necessary (summarized in Ambrose, Bridges, DiPietero, Lovett, & Norman, 2010).

Self-regulation and motivation, two factors that influence student learning, are tied to metacognition. A major goal of education is to create self-regulated learners, students who understand how they learn and take responsibility for their learning. Metacognition is closely related to learning regulation (Dinsmore, Alexander, & Loughlin, 2008) and has been implicated as a distinguishing factor of "expert students" (Sternberg, 1998). Metacognition is also connected to student motivation. Students with developed metacognitive skills take ownership of their learning to be active learners (Zull, 2011). This active process makes learning more enjoyable and more effective (Georghiades, 2000). Considerable evidence has shown the positive impact of metacognition activity on student thinking (Gunstone, 1991; Adey & Shayer, 1994) and a positive correlation between metacognitive awareness and student learning at both the secondary and college levels (Wang, Haertel, & Walberg, 1990; Young & Fry, 2008). Metacognitive instruction also promotes scientific literacy by improving concept durability and the transfer of scientific knowledge from school to outside the classroom (Ormrod, 2011).

Teaching science as inquiry (TSI)

TSI philosophy is grounded in the ideas of disciplines of knowledge (King & Brownell, 1966) and disciplinary inquiry (Pottenger, 2007). Within the discipline of science, a community of scientists shares a common set of practices and demeanors when participating in scientific inquiry. In a TSI classroom, teachers and students are linked as part of a disciplinary community of knowledge generation (Pottenger, 2007; Seraphin, & Baumgartner, 2010). Students are expected to act as scientists, engaging in scientific practices such as asking questions, collecting, analyzing, and interpreting data, communicating, contributing to the community, and exhibiting the demeanors of professional scientists, such as honesty, responsibility, and open-mindedness. Because TSI emphasizes the nature of science, importance is placed on learning about scientific processes (e.g. what scientists do) in the context of scientific findings (e.g. what scientists know).

TSI encompasses cycles of both learning and instruction. These cycles are reflected in phases, which represent different aspects of the inquiry process. The five phases of the TSI model are *initiation, invention, investigation, interpretation,* and *instruction*. *Initiation* is a phase of originating interest or developing a focus for inquiry. This may come in the form of a student asking a question or a teacher posing a problem. The *invention* phase entails problem solving and information gathering, including creating a testable hypothesis, designing an experiment, or troubleshooting a procedural step. Students engage in *investigation* as they gather new knowledge through carrying out tests or analyzing data. Information gathered during investigation requires *interpretation*, evaluating results and conclusions through both a reflective, internal process and an objective, external process. *Instruction* is integral to each phase. Instruction is broadly defined in the TSI model and includes communication from teacher-to-student, student-to-student, and student-to-teacher. Like other learning cycles, the TSI phases are represented in a circular model (see Bybee et al., 2006). Unlike other learning cycles, TSI refutes a lockstep sequence through the cycle and promotes fluidity between the phases. In addition, instruction–with its many nuances–surrounds and influences the other phases, creating an environment where the teacher acts as the leader and research director but not the sole source of knowledge in the classroom (see Figure 1).

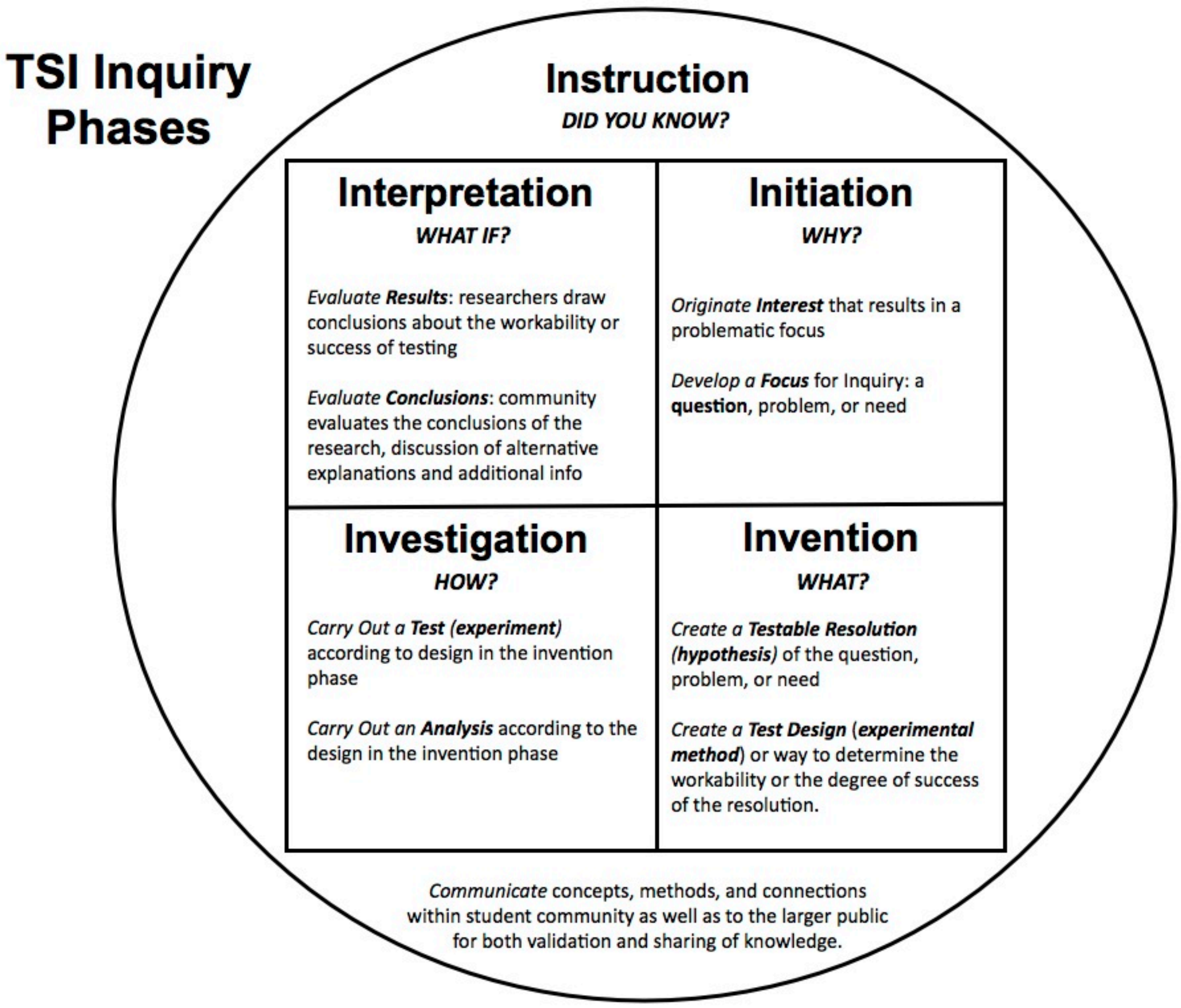

Figure 1. TSI Inquiry Phases

The TSI square-in-circle phase diagram, which lacks arrows, provides an area for each phase to connect with each of the other phases to illustrate the interconnected nature of the five phases of inquiry. The instruction phase encircles the other phases, emphasizing the role of communication in teaching and learning through inquiry.

The square-in-circle diagram of the TSI phases reflects our understanding of the nature of the process of science. The arrangement of the phases, which are connected but not sequential, emphasises the possibility of multiple logical progressions rather than rigid, linear, procedural steps. For example, *initiation* can occur at the beginning of a lesson, but it can also occur throughout the course of *investigation* as students re-initiate by experiencing anomalies, asking questions, or considering new information. An encountered difficulty in *interpretation* can redirect the learning cycle, leading to the need for *invention* of new processes or ideas to be investigated. Alternatively, *investigation* may spark an entirely new learning cycle, composed of new questions, materials, and investigations. The encompassing *instruction* phase can occur throughout the other phases, as a teacher prompts students to consider alternate conceptions or methods, as students communicate and share information with each other, or when students present their findings outside the classroom. Students may move fluidly through the phases as individuals, pairs, or groups, while the whole class community progresses through a larger cycle of learning, moving toward clearer understandings of scientific concepts. The flexibility of the TSI cycle thus reflects not only what happens in an authentic scientific process, but also what happens in a classroom setting (Seraphin & Baumgartner, 2010).

Table 1. The Modes of Inquiry Addressed in TSI (modified from Seraphin, Philippoff, Parisky, Degnan, & Papini Waren, 2012)

Mode (Inquiry learning through use of …)	Description (Search for new knowledge …)
Curiosity	in external environments through informal or spontaneous probes into the unknown or predictable
Description	through creation of accurate and adequate representation of things or events
Authoritative knowledge	through discovery and evaluation of established knowledge via artifacts or expert testimony
Experimentation	through testing predictions derived from hypotheses
Product Evaluation	about the capacity of products of technology to meet valuing criteria
Technology	in satisfaction of a need through construction, production and testing of artifacts, systems, and techniques
Replication	by validating inquiry through duplication; testing the repeatability of something seen or described
Induction	in data patterns and generalizable relationships in data association – a hypothesis finding process
Deduction	in logical synthesis of ideas and evidence – a hypothesis making process
Transitive knowledge	in one field by applying knowledge from another field in a novel way

Modes are used in the TSI framework to reflect the variety of ways to do scientific inquiry. Whereas phases define the stages of the inquiry cycle, modes describe the multiple approaches to knowledge generation and acquisition, an important aspect of disciplinary inquiry (see Windschitl, Dvornich, Ryken, Tudor, & Koehler, 2007). Investigating various aspects of the nature of science and using evidence from a variety of sources can lead to conceptual change in science understanding (Tytler, 2002; Zembel-Saul et al., 2002).

Research on the process of knowledge development, therefore, supports the use of multiples modes of inquiry. TSI emphasizes modes as different ways of carrying out scientific processes, challenging the widely held misconception that all inquiry is hands-on and all hands-on activities are inquiry (see Rankin, 2000). For example, even though *experimentation* is often equated with inquiry, the TSI framework argues that each of the other modes, including *authoritative knowledge*, are an important means by which to access information in scientific inquiry. In addition, although some modes and phases are well suited to each other, such as *instruction* and *authoritative knowledge,* or *initiation* and *curiosity*, any mode can be employed in any phase. For example, *description*, *induction*, *deduction*, and *transitive knowledge* are often important modes in the *instruction* phase. The TSI modes of inquiry are detailed in Table 1.

TSI and metacognition

Although not explicitly addressed in the theoretical framework of TSI (Pottenger, 2007), we have found metacognition to play a key role in teaching and learning science through inquiry. Inquiry-based learning has been associated with improving student self-regulation (Schraw et al., 2006), which is linked to metacognitive abilities (Dinsmore et al., 2008; Schraw et al., 2006). The TSI framework balances content, context, inquiry, and pedagogy, and creates a classroom setting that fosters self-regulation and intentional learning, a crucial element of effective learners. Intentional learners are able to actively integrate new information with their own awareness of how they make sense of this new information; they are fueled by motivation and eagerness to learn: and, perhaps most importantly, they are understand and expect that knowledge about a topic continues to evolve and that mastery takes significant time, considerable effort, and perseverance (Ormrod, 2011). Self-regulated, intentional learners are in charge of, and responsible for, much of their learning, using elements of inquiry and metacognition to help guide their thinking.

The TSI pedagogical framework focuses on learning through the authentic application of knowledge and skills. The framework is designed to help teachers teach both the processes and content of science, which according to Edelson (1999), enables students to better apply what they have learned in real-word situations. When teachers effectively teach science through TSI-based inquiry, they guide students' reasoning through the judicious use of discussion, insight, and assistance. Teachers help students evaluate and decide which inquiry techniques to use during their investigations through a process of self-regulation. Using this inquiry- and process-based approach to science teaching, teachers help students develop the two main components of metacognition, awareness and control of their thought processes.

Our understanding of the role that metacognition plays in creating self-directed, intentional learners, and the connection between inquiry and metacognition, has led us to incorporate explicit discussion, activities, examples, and modeling of metacognition in the TSI PD. A number of studies have examined ways to improve metacognition through classroom instruction and have suggested that metacognition can be improved by direct instruction and modeling of metacognitive strategies (e.g. Gunstone & Mitchell, 1998; Mason, 1994). Working under this premise, and the idea that students can be taught to monitor their understanding in order to improve learning gains (see Baird, 1986; Bielaczyc, Pirolli, & Brown, 1995; Chi DeLeeuw, Chiu, & LaVancher, 1994; Paliscar & Brown, 1984), we have extended the PD component of metacognition to the teachers' classrooms. As part of the TSI PD experience, teachers follow the instruction and modeling exemplified in the workshops as they teach students to be metacognitive in their science studies.

TSI aquatic professional development: program features.

We are currently developing and evaluating a year-long, place-based aquatic science TSI PD that enables teachers to teach aquatic science concepts through the disciplines of physics, chemistry, biology, and ecology. This course, called TSI Aquatic, is presented in four modules (see Figure 2) and has contact hours approximating a two-week training (84 hours). The PD also has an integrated online learning community component. Each of the four TSI Aquatic modules consists of an intensive two-day workshop (16 hours), a face-to-face follow-up session (3 hours), and an online sharing session (2 hours). This paper presents results from the 2011-2012 cohorts, which are helping to shape the 2012-2013 PD. During the 2011-2012 school year, 28 teachers from the Hawaiian islands of Maui, Lana‘i, Moloka‘i, and Hawai‘i participated in the TSI Aquatic course.

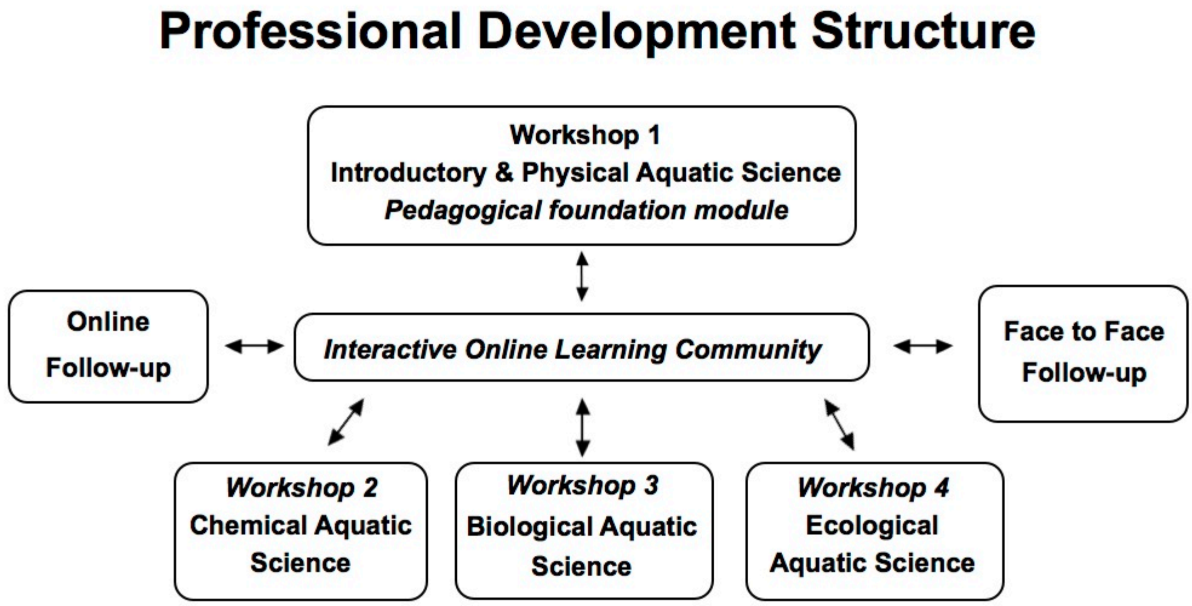

Figure 2. Professional Development Structure

TSI professional development structure illustrating the sequence of, and links between, PD components. After an introductory session, the PD progresses through four disciplinary module iterations, each consisting of a workshop, a face-to-face follow-up and an online follow-up. Modules are embedded in, and connected through, an interactive online learning community.

Metacognition in the TSI aquatic PD

Metacognitive processes can be both domain-general and domain-specific (Sternberg, 1998), but with respect to scientific inquiry, we believe that the context of metacognition is important. For this reason, we introduced metacognition as one of the primary focuses for Module 1, and we defined metacognition within the context of the first workshop activity, an open-ended investigation of density. After acknowledging the teachers’ range of content and inquiry knowledge, the contextualized metacognition activity was used to establish the expectation that all of the teachers in the PD gain a deeper understanding of the process of science by using their metacognitive skills during the activities. As a result, not only were teachers of diverse backgrounds engaged, but a clear expectation was also established– that teachers were to become more metacognitive as a result of their experiences in the PD.

Following the open-ended, metacognition density activity, teachers rotated through a series of inquiry stations designed to stimulate discussion about how people learn. Each station used a different approach to present the topic of density as related to ocean circulation. The stations were based on an activity from the University of California Berkley's Lawrence Hall of Science Communicating Ocean Science (COS) course, developed in partnership with the Centers for Ocean Science Education Excellence–California and Island Earth (COSEE-CA and COSEE-IE). As teachers engaged in each inquiry station, they were challenged to think about how their learning experience was impacted by the design of the station. After the series of activities, PD facilitators led a discussion about participants' experiences and thoughts, helping teachers to compare the strengths of various pedagogical approaches. This discussion was used to introduce the TSI phases of inquiry. We also discussed how this type of metacognitive strategy development (e.g. explicit instruction, modeling, and application) has been shown to be successful in learning and teaching, particularly when combining several interrelated strategies for solving problems (Bruning, Schraw, & Norby, 2011).

The inquiry stations were also used to introduce TSI-based lesson planning, via the TSI phases, at multiple levels. We discussed the idea that, throughout a learning progression, individual lessons may target a particular TSI phase, whereas in one lesson, whereas in on particular lesson, each of the TSI phases may occur throughout aspects of that lesson. To demonstrate how TSI can be used to examine the fine-scale acquisition of knowledge through metacognitive scientific inquiry, teachers were asked to write down, in order, each of their actions and thoughts from one of the inquiry learning stations. After recounting their physical and mental steps, teachers aligned each step with a TSI phase. Teachers then drew arrows on the TSI phase diagram (see Figure 1) to indicate the progression of their learning and thinking processes. The purpose of this exercise was to connect teachers' metacognitive thinking with their thoughts and actions and to demonstrate the multi-directional process of knowledge acquisition and the scientific process. Because the circle-in-square arrangement of TSI phases has no prescribed sequence or path, teachers were able to indicate their individual cognitive paths on the reflective diagram. The ensuing discussion in the PD highlighted the fact that, although teachers may design a lesson to move through a particular sequence of TSI phases, each student's cognitive process flow will be unique. Throughout the Module 1 workshop, teachers were asked to reflect on their thought processes using the TSI phase diagram, and they were encouraged to use the TSI phase and mode words to facilitate discussion of the scientific process.

TSI classroom implementation

Being able to recognize where students are in the TSI phases during the learning processes can help teachers to re-direct, or re-initiate, students to accomplish lesson goals. This is especially useful when students are "stuck" in a particular phase, which prevents their progression toward conceptual understanding. As they implemented Module 1 lessons in their classroom, teachers were asked to use the TSI phase diagram to help them observe a group of students and infer the students' metacognitive processes. In Module 2, teachers wrote a narrative describing their TSI phase diagrams using the language of the TSI phases and modes to facilitate understanding, interpretation, and explanation of the nuances of activity implementation.

In Module 3, teachers were asked to teach the TSI phases to their students via a metacognition activity. In this exercise, which mirrored the introduction of phases that teachers completed in the Module 1 PD, students wrote their action and thought steps after an activity, categorized these actions and thoughts into TSI phases, and completed a reflective TSI phase diagram.

The purpose of this activity was the same for students as for teachers–to help build students' awareness of their learning and the relationship of learning to the dynamic scientific process. In addition, the activity provided students with the vocabulary to talk about inquiry as they navigate through the scientific process in their classroom.

Starting in Module 4, teachers planned their lessons using the TSI phases. Teachers also repeated the metacognition activity with their students, this time including the TSI modes in addition to the phases. By the end of the four modules in the TSI Aquatic series, teachers had implemented eight activities (two per module), reflected on their use of the TSI phases and modes in each activity, and taught their students the phases and modes.

Other research instruments

In addition to filling out TSI lesson plans and reflections for each activity, teachers completed a pre-post PD pedagogical content knowledge and self-efficacy questionnaire, a pre-post pedagogy of science teaching assessment, and a post-project interview. Teachers also wrote one inquiry free-write (three-minutes) per module, in which they were asked to describe what inquiry meant to them and what inquiry looked like in a classroom. Although not specifically targeted to assess metacognitive skills, analysis of teachers' responses on the set of instruments provides additional evidence of PD impact on teachers' understanding of the scientific process and classroom implementation of inquiry. To assess the impact of the PD on student understanding of the process of science, students were given pre-post PD nature of science questionnaires.

Preliminary results: TSI lesson plans and reflection

The reflective TSI phase diagram allowed teachers to demonstrate their understanding of the non-linear process of science. By carefully observing and documenting a group of students, teachers showed new awareness of the nuances of the scientific process in their classroom. For example, one teacher drew very simple, mostly linear phase diagrams in Module 1, but by Module 3 the number of arrows, and the teachers' recognition of the nuances of students' cognitive processes, appeared to have increased. The teachers' diagrams also showed a more flexible use of the phases as the PD progressed. This understanding of the fluid cognitive movement between phases was described by one teacher as "students moved into the investigation stage when they worked on [the] worksheet…This activity had a lot of discussion which moved them into the instructional phase…They moved into interpretation as they decided on a final answer, as they were doing this they moved into instruction as well, with much discussion…". By the end of the program, teachers seemed to have a better understanding of the fluid and multidirectional nature of scientific inquiry, describing how students engaged in learning "move in and out of the phases and just keep going."

The reflective TSI phase diagram and narrative gave teachers the opportunity to utilize their metacognitive skills and critically observe their students process of knowledge acquisition. Categorizing classroom events into TSI phases through the use of diagrams and reflections provided a format for teachers to communicate how their students acquired knowledge during an activity (see Figure 3). Teachers recognized the value of the TSI phase diagram as a pedagogical tool to monitor student learning. One teacher commented that she "noticed that most students spent the majority of their time in the investigation/interpretation phases because they were continually trying new tests and evaluating their work." She went on to say, "I would have encouraged this [alternation between investigation and interpretation] if I had not seen it," indicating that her observation of students' thought processes allowed her to not only observe, but also to assess and modify her role as instructor by documenting her students' progression through the TSI phases of inquiry, ultimately helping her achieve her teaching goals.

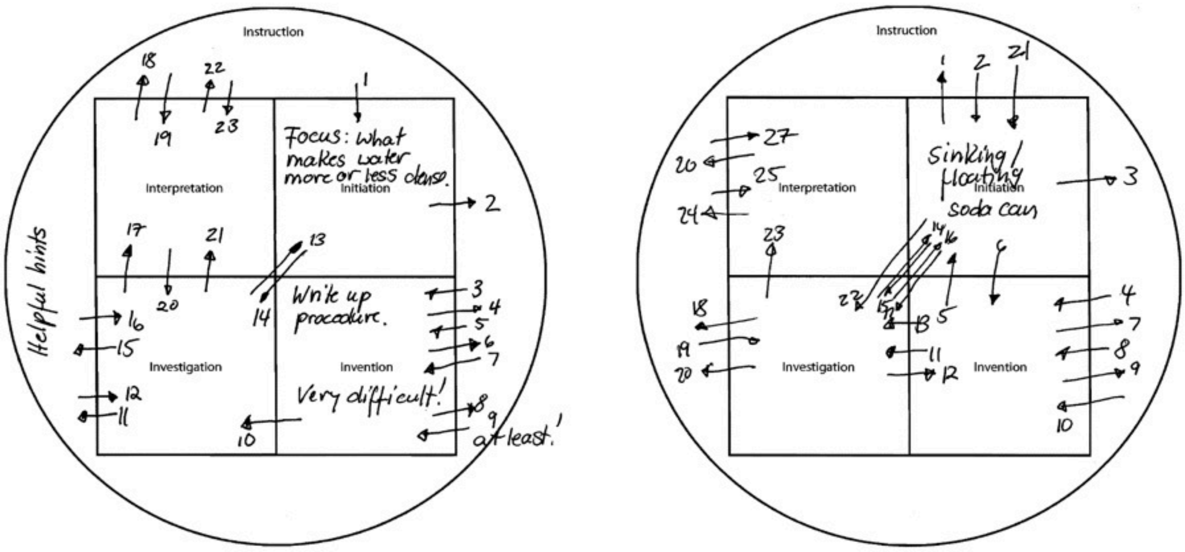

Figure 3. Categorizing classroom events into TSI phases through the use of diagrams and reflections

Examples of one teacher's reflective TSI phase diagrams from two lessons on density. These diagrams illustrate the teacher's perception of the students' progression through the stages of inquiry. Although both lessons begin with *initiation* and end with *interpretation*, the diagrams show the multi-directional and nuanced links between the phases and how important *instruction* is when engaging in inquiry.

In addition, there was evidence that teachers with lower science content knowledge developed a deeper, richer understanding of scientific inquiry through thoughtful reflective phase diagram completion and explicit use of phases and modes in their reflection narratives. For example, teachers tended to begin the PD with the assumption that instruction requires the teacher, and they moved toward categorizing instruction as "students completing lab questions together" and "(planned) student to student discussion." However, there was also evidence that over time teachers became less thoughtful in their completion of the lesson reflections, especially if they considered themselves to be seasoned inquiry practitioners. We attribute this to "phase diagram burnout," which is understandable given that teachers completed at least eight reflective templates throughout the course of the PD.

Preliminary analysis of the lesson reflections showed lingering misconceptions about TSI philosophy. For example, on a Module 3 reflection one teacher failed to mark her class' time in the initiation phase, writing in her reflection "We also came back several times to the initial questions, but I did not mark these arrows [because] I am unsure if coming back to the initial question is the same as coming back to the initiation phase". In addition, as found in other TSI PD courses (see Seraphin et al., 2012), we found that teachers often eschew the authoritative mode even after explicit discussion of how direct instruction is a valuable aspect of inquiry. Avoiding identifying this mode in their classroom may be due to strongly held misconceptions that lecturing is not a way to engage in inquiry. Although the authoritative mode was rarely specified, teachers wrote in their narratives that they provided direct instruction to their students, indicating they had engaged in this mode.

TSI with students

In Module 3, many teachers and students initially had trouble with the metacognition activity. One teacher described this struggle; "The most difficult part of this lesson was getting students to think about their thinking. It was difficult to explain as there is SO much to it– just like it was for us when we learned it…so I felt their pain, but I also know that as they get familiar with it, it will become easier." Some teachers dealt with this difficulty by circumventing the intent of the activity; they described and assigned TSI phases to specific portions of an activity rather than allowing their students to recognize and categorize their own actions and thoughts. Other teachers supported student understanding by teaching the TSI phases as science vocabulary words, sharing examples of their own reflective TSI phase diagrams with their students, and allowing students to work together in preparing student-generated phase diagrams. These teachers noted that once students "got the hang of it (they) started talk[ing] about how interesting it was that they spent a lot of time in one or the other phases."

When teachers repeated the metacognition activity in Module 4, students were more familiar with the language of TSI and the process of the activity. One teacher noted that this time "following the procedures for the metacognition activity made guiding students through the TSI phases much simpler. Students wrote their thoughts and actions down. They are improving their written communication, but they still have room to improve on details. I handed out the worksheet identifying the different phases of instruction, initiation, invention, investigation, and interpretation. At this point, matching up the TSI phases [with their thoughts and actions] was much more obvious for most students."

Other research instruments

Our qualitative findings are supported by preliminary data analyses from two teacher questionnaires, the Self-Efficacy in Science Questionnaire (SFQ), and the Pedagogical Content Knowledge Questionnaire (PCK). In addition we analyzed results from a student questionnaire, the Student Nature of Science Questionnaire (NOS). The purpose of the SFQ was to find out the degree to which teachers' changed in their self-reported abilities about teaching science as inquiry. The SFQ was given as a retrospective pre-post questionnaire (Lawton, 2005), and a paired-samples t-test was conducted to see if there was a gain in teachers' scores on the SFQ. Because not all the teachers were available to complete both the pre and the post, out of the 28 teachers that participated in the PD, 25 completed the SFQ, $N = 25$. There was a statistically significant increase in teachers' SFQ pre-PD scores ($M = 3.53$, $SD = 0.85$) to post-PD scores ($M = 4.73$, $SD = 0.81$), t (9.28), $p < .001$.

The purpose of the PCK was to find out the degree to which teachers' changed in their self-reported pedagogical practices. The PCK was given as a pre- and post-PD questionnaire (Scarlett, 2008), and a paired-samples t-test was conducted to see of there was a gain in teachers' scores on the PCK. Because not all the teachers were available to complete both the pre and the post, out of the 28 teachers that participated in the PD, 24 completed the PCK, $N = 24$. There was not a statistically significant increase in teachers' PCK pre-PD scores ($M = 3.76$, $SD = 0.42$) to post-PD scores ($M = 3.85$, $SD = 0.33$), t (1.3), $p = 0.206$, but the effect size was positive with a Cohen's d of 0.24.

The purpose of the NOS was to find out the degree to which students' changed in their understandings of the nature of science. The NOS was given as a pre- and post-PD questionnaire, and paired-samples t-test was conducted to see of there was a gain in students' scores on the NOS. Of the 648 students in the cohort, we report results from consenting students who completed both the pre- and post PD questionnaire, $N = 342$. There was a statistically significant increase in students' NOS pre-PD scores ($M = 12.40$, $SD = 3.61$) to post-PD scores ($M = 13.13$, $SD = 3.89$), t (9.28), $p < .001$.

Lastly, the qualitative instrument Teacher Inquiry Free-writes (TIFs) has to date showed little evidence of inquiry understanding or growth. Reasons for this lack of growth may in part be due to the limited time allotted to this activity and reflection fatigue as teachers were asked to describe their knowledge of inquiry multiple times during each module.

Discussion

The disciplinary form of inquiry-based teaching espoused by the TSI philosophy advocates students learning science concepts through the process of doing science. We followed this principle by teaching metacognition through aquatic science content, using context to generate the thought processes needed for metacognitive reflection. The TSI Aquatic format of a year-long, modular PD permitted the scaffolding of metacognitive strategies and TSI pedagogy, including the use of the language of the TSI phases and modes, along with implementation and reflection components.

Although the capability to use metacognitive strategies generally develops with age and increasing prior knowledge (Brown & DeLoache, 1978), students and teachers vary in metacognitive ability. Prior to the TSI Aquatic PD, use of metacognitive strategies was not a familiar component of our participant teachers' practice. At the start of Module 1, it was common for both new and seasoned teachers to be unfamiliar with the concept of metacognition. Before our teachers could help their students become more metacognitive, they needed to understand the significant role that awareness and control of one's thought processes plays in understanding the scientific process and acquiring scientific knowledge. We began this process by acknowledging that students at all levels, including teachers, have room to improve their assessment of their skills and knowledge and manage of their learning abilities (Brown, Bransford, Campione, & Ferrara, 1983; Hacker et al., 2000; Kruger & Dunning, 1999; Pascarella & Terenzini, 2005). Using this perspective, we were able to create a community of teachers, from various backgrounds, content knowledge levels, and pedagogical experience, focused on using metacognition to better their teaching practice in order to more effectively teach science as a discipline.

Previous research has indicated that metacognitive skills are difficult to report and assess because they often develop in the absence of conscious reflection (Schraw et al., 2006). The TSI Aquatic PD gave teachers, and their students, a common language to communicate the process of science. The TSI terminology, together with the unique reflective TSI phase diagram, generated an awareness, through critical observation and reflection, of the multi-directional process of knowledge acquisition that occurs during a classroom inquiry. This awareness of thought processes is a crucial component in becoming more metacognitive (see Schraw et al., 2006), and is a factor in the development of self-regulation skills as students with better self-regulation skills are able to learn more efficiently and report higher levels of academic satisfaction (Pintrich, 2000; Zimmerman, 2000).

As teachers became more comfortable with the TSI vocabulary and their understanding of the TSI phases and modes, they were able to able to recognize not only where their students were in the TSI phases, but they were also able to evaluate their student's progression and direct them through the phases to enhance learning. Thus teachers' metacognitive abilities were enhanced through the PD by scaffolding metacognitive skills, starting with reflection and recognition of the complex process of science and building towards an application and regulation of their behavior to achieve lesson goals. This is reflected in preliminary results of pre-post surveys, which indicate pedagogical gains for both teachers and students.

Considerable evidence has shown the positive impact of metacognitive activity on student thinking (Gunstone, 1991; Adey & Shayer, 1994). Our classroom reflection data from teachers provides additional evidence of the positive impacts of teaching metacognition within the context of scientific inquiry. Although often difficult to teach to students, with patience, effort, and repetition teaching metacognitive strategies through the use of TSI appeared to help improve students' understanding of the scientific process, students' ability to actively engage in the scientific process using metacognition, as well as students' content knowledge. These results support our previous work implementing the TSI pedagogical framework in other disciplines (e.g. energy, astronomy, and density) over shorter time spans (equivalent to one module of TSI Aquatic). These shorter workshops have shown positive gains in teachers' knowledge and implementation of inquiry in their classroom (see Seraphin et al., 2012).

One of the most significant outcomes we observed from our approach of teaching metacognitive skills through TSI pedagogy was that teachers and students can improve their ability to evaluate their cognitive strengths and weaknesses and to learn to use that knowledge strategically. Indeed, our results suggest that both novice and seasoned teachers benefit from metacognition-focused science inquiry PD. Observed teacher and student gains were achieved through a combination of explicit instruction, modeling, discussion, activities, and implementation throughout the TSI Aquatic PD and replicated in the teachers' classrooms. The philosophy of TSI and corresponding phase and mode framework allowed us to build a common language in the PD that translated to the classroom. Teacher reflections indicated that language of TSI was effective in allowing teachers and students to discuss, and ultimately assess, their own metacognition.

Future directions & recommendations

Our current findings suggest that metacognition is a valuable addition to both teacher PD and classroom instruction. Our results also indicate that teachers need to be supported in their metacognitive development. We feel it is important that both PD facilitators and teachers recognize that metacognition grows gradually; it is a process that requires patience and time. Teachers need to be taught metacognitive strategies, but they also need sufficient time to practice these strategies in a PD before they are asked to teach them to their students.

Based on this premise and our preliminary results, we are modifying our implementation of metacognition, and the associated instruments, in the TSI Aquatic PD. These changes are being implemented with 31 teachers from O‘ahu and Kaua‘i enrolled in the course for the school year 2012-2013. In this iteration of the PD, more time will be spent discussing, differentiating, and defining the TSI phases and modes to clarify understanding. More time will also be allocated for feedback from both PD facilitators and peers on TSI reflections, including phase diagrams and other classroom implementation requirements. We hope that sharing in this way will allow peers to correct and support each other while workshop facilitators are nearby to answer questions, address misconceptions, and individually instruct if necessary.

The TSI phases and reflective diagrams appear to be a powerful tool to teach metacognitive reflection and show the multi-directional process of inquiry. However, the act of diagramming seems to lose utility once teachers have experienced tracking their thought processes and their students' progress through the phases of inquiry a few times. In our revised PD, we are reducing diagramming requirements and focusing more on using the TSI framework in planning and teaching students to be metacognitive learners. The metacognition activity, in which teachers are required to teach their students the TSI phases and modes, will also be moved earlier in the PD sequence to allow for more classroom repetition. In order for teacher inquiry free-writes to serve as a more useful metacognition instrument, we are decreasing the number of times they will be used, but extending the time allotted for each reflection.

Lastly, to directly assess the impact of the PD on metacognition and learning, we have adapted a subset of five statements from the Metacognition Awareness Inventory (MAI), (Schraw & Dennison, 1994) and added these to pre-post PD questionnaires for both teachers and students. In addition, teachers will respond pre-post PD to ten statements from the MAI-T, an adaptation of the MAI designed specifically for teachers (Balcikanli, 2011). Classroom observations will also be added as a means to ground teacher reflections on classroom implementation and as a method for observing teacher and student growth in the application of metacognition in inquiry science learning.

We believe that science education should strive to teach science as inquiry, promote metacognition, and be mindful of the development of epistemic beliefs consistent with effective learning strategies. To that end, we advocate both the explicit scaffolding of metacognitive strategies in PD with teachers and the extension of these strategies from teachers to their students. We believe that scientific literacy is enhanced when students use their metacognitive skills to think critically about, while engaging in, the scientific process.

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References

Adey, P. and Shayer, M. (1994). *Really Raising Standards.* London: Routledge.

Ambrose, S. A., Bridges, M. W., DiPietro, M., Lovett, M. C., & Norman, M. K. (2010). *How Learning Works: Seven Research-Based Principles for Smart Teaching.*
San Francisco, CA: Jossey-Bass.

Balcikanli, C. (2011). Metacognitive awareness inventory for teachers (MAIT). *Electronic Journal of Research in Educational Psychology*, *9*(3), 1309-1332.

Baird, J. (1986). Improving learning through enhanced metacognition: A classroom study. *European Journal of Science Education, 8*(3), 263-282.

Bielazyc, K., Pirolli, P. L., & Brown, A. L. (1995). Training in self-explanation and self-regulation strategies: Investigating the effects of knowledge acquisition activities on problem solving. *Cognition and Instruction*, *13*(2), 221-252.

Brown, A. (1987). 'Metacognition, executive control, self-regulation and other more mysterious mechanisms.' In: WEINERT, F. and KLUWE, R. (Eds) *Metacognition, Motivation and Understanding*. Hillsdale, NJ: Erlbaum, pp. 65–116.

Brown, A. L., Bransford, J. D., Campione, J. C, & Ferrara, R. A. (1983). Learning, remembering and understanding. In J. Flavell & E. Markman (Eds.), Handbook of child psychology, *Cognitive Development*, *3*, 77-166. New York: Wiley.

Brown, A. L., & DeLoache, J. S. (1978). Skills, plans and self-regulation.

In R. S. Siegier (Ed.), *Children's thinking: What develops?* Hillsdale, N J: Erlbaum.

Bruning, R. H., Schraw, G. J., & Norby, M. M. (2011). Cognitive Psychology and Instruction (5th ed.). Upper Saddle River, NJ: Pearson.

Bybee, R. W., Taylor, J. A. Gardner, A., Van Scotter, P. Powell, J. C., Westbrook, A., & Landes, N. (2006). *The BSCS 5E Instructional Model: Origins and Effectiveness. A Report Prepared for the Office of Science Education National Institutes of Health.* Colorado Springs, CO: BSCS. Retrieved from http://science.education.nih.gov/houseofreps.nsf/b82d55fa138783c2852572c9004f5566/$FILE/Appendix%20D.pdf

Carey, S., & Smith, C. (1993). On understanding the nature of scientific knowledge. *Educational Psychologist, 28(3),* 235-251.

Chi, M. T. H., DeLeeuw, N., Chiu, M.-H., & LaVancher, C. (1994). Eliciting self-explanations improves understanding. *Cognitive Science, 18*, 439-477.

Dinsmore, D. L., Alexander, P. A., & Loughlin, S. M. (2008). Focusing the conceptual lens on metacognition, self-regulation, and self-regulated learning. *Educational Psychology Review*, *20*, 391-409.

Seraphin, K., & Baumgartner, E. (2010). Students as scientists: guidelines for teaching science through disciplinary inquiry. In R. Yager (Ed.), *Exemplary Science for Resolving Societal Challenges* (pp. 33-50). Arlington, VA: National Science Teachers Association–NSTA Press.

Seraphin, K., J. Philippoff, A. Parisky, K. Degnan, & D. Papini Waren. (2012). Teaching Energy Science as Inquiry: reflections on professional development as a tool to build inquiry teaching skills for middle and high school teachers. *Journal of Science Education and Technology*. 1-17. DOI 10.1007/s10956-012-9389-5

Edelson, D. C., Gordin, D. N., & Pea, R. D. (1999). Addressing the Challenges of Inquiry-Based Learning through Technology and Curriculum Design. *The Journal of the Learning Sciences*, *8*(3), 391-450.

Flavell, J.H. (1976). Metacognitive aspects of problem solving. In L.B. Resnick (Ed.), *The nature of intelligence* (pp. 231-235). Hillsdale, NJ: Erlbaum.

Georghiades, P. (2000). Beyond conceptual change learning in science education: focusing on transfer, durability, and metacognition. *Education Research*, *42*(2), 119-139.

Gunstone, R. F. (1991). 'Constructivism and metacognition: theoretical issues and classroom studies.' In: DUIT, R., GOLDBERG, F. and NIEDDERER, H. (Eds) *Research in Physics Learning: Theoretical Issues and Empirical Studies.* Bremen: IPN, pp. 129–140.

Gunstone, R., & Mitchell, I. J. (1998). Metacognition and conceptual change. In J. L. Mintzes, J. H. Wandersee, & J. D. Noval (Eds.), *Teaching for science education: A human constructivist view* (pp. 133–163). San Diego, CA: Academic Press.

Hacker, D. J., Bol, L., Horgan, D. D., & Rakow, E. A. (2000). Test prediction and performance in a classroom context. *Journal of Educational Psychology*, *92*(1), 160-170.

Hammer, D. (1999). *Teacher Inquiry*. Center for the Development of Teaching Paper Series. Report: ED433997. 25pp.

King, A.R., Jr., & Brownell, J.A. (1966). *A Theory of Curriculum Practice.* New York, NY. John Wiley and Sons, Inc.

Kruger, J., & Dunning, D. (1999). Unskilled and unaware of it: how difficulties in recognizing one's own incompetence lead to inflated self-assessments. *Journal of Personality and Social Psychology*, *77*(6), 1121-1134.

Lawton, B. E. (2005). *The differential effects of two versions of middle-school inquiry-based science program professional development institutes on teachers' self-efficacy as inquiry-based science teachers*. Paper presented at the annual meeting of the American Educational Research Association, Montreal, Canada.

Mason, L. (1994). Cognitive and metacognitive aspects in conceptual change by analogy. *Instructional Science*, *22*(3), 157–187.

National Research Council (1996) *National Science Education Standards*. National Academy Press, Washington, DC.

National Research Council (2001). *Knowing what students know: The science and design of educational assessment.* Committee on the Foundations of Assessment, J. Pellegrino, R. Glaser, & N. Chudowsky (Eds.). Washington, DC: National Academy Press.

Ormrod, J. E. (2011). *Human Learning* (6th ed.). Upper Saddle River, NJ: Prentice Hall.

Palinscar, A. S., & Brown, A. L. (1984). Reciprocal teaching of comprehension-fostering and comprehension-monitoring activities. *Cognition and Instruction*, *1*(2), 117-175.

Pascarella, E. T., and Terenzini, P. T. (2005). *How college affects students: A third decade of research* (Vol. 3), Jossey-Bass, San Francisco.

Pintrich, P. (2000). The role of goal orientation in self-regulated learning. In M. Boekaerts, P. Pintrich, & M. Zeidner (Eds.), *Handbook of self-regulation* (pp. 452–501). San Diego, CA: Academic Press.

Pottenger, F.M. (2007, January). *Inquiry and disciplinary natural science teaching*. Paper presented at the Hawaiʻi International Conference on Education, Honolulu, HI.

Rankin, L. (2000). Lessons learned: Addressing common misconceptions about inquiry. In *Foundations: A monograph for professionals in science, mathematics, and technology education: Inquiry: Thoughts, views, and strategies for the K–5 classroom* (Vol. 2, pp. 33-37). Retrieved from http://www.nsf.gov/pubs/2000/nsf99148/pdf/nsf99148.pdf

Scarlett, T. (2008). *An exploratory study of the impact of two versions of inquiry-based science program professional development on teachers' perceptions of their pedagogical content knowledge*. (Doctoral dissertation). Retrieved from ProQuest Dissertations and Theses database. (Accession No. 304603723)

Schraw, G., Crippen, K. J., & Hartley, K. (2006). Promoting self-regulation in science education: Metacognition as part of a broader perspective in learning. *Research in Science Education*, *36*(1-2), 111-139.

Schraw, G., & Dennison, R. S. (1994). Assessing metacognitive awareness. *Contemporary Educational Psychology*, *19*, 460-475.

Smith, C. L., Maclin, D., Houghton, C., & Hennessey, M. G. (2000). Sixth-grade students' epistemologies of science: the impact of school science experiences on epistemological development. *Cognition and Instruction*, *18*(3), 349-422.

Smith, C. L., & Wenk, L. (2006). Relations among three aspects of first-year college students' epistemologies of science. *Journal of Research in Science Teaching*, *43*(8), 747-785.

Sternberg, R. J. (1998). Metacognition, abilities, and developing expertise: what makes an expert student?. *Instructional Science*, *26*(1-2), 127-140.

Tytler, R. (2002). Teaching for understanding in science: constructivist/conceptual change teaching approaches. *Australian Science Teachers' Journal, 48*(4), 30-35.

Wang, M. C., Haertel, G. D., & Walberg, H. J. (1990). What influences learning? a content analysis of review literature. *The Journal of Educational Research*, *84*(1), 30-43.

Wee, B., Shephardson, D., Fast, J., & Harbor, J. (2007). Teaching and learning about inquiry: Insights and challenges in professional development. *Journal of Science Teacher Education*, *18*(1), 63-89.

Windschitl, M., Dvornich, K., Ryken, A.E., Tudor, M., & Koehler, G. (2007). A comparative model of field investigations: Aligning school science inquiry with the practices of contemporary science. *School Science and Mathematics, 107*(1)*,* 382-390.

Young, A., & Fry, J. D. (2008). Metacognitive awareness and academic achievement in college students. *Journal of the Scholarship of Teaching and Learning*, *8*(2), 1-10.

Zembel-Saul, C., Munford, D., Crawford, B., Friedrichsen, P., & Land, S. (2002). Scaffolding preservice science teachers' evidence-based arguments during an investigation of natural selection. *Research in Science Education, 32*(4)*,* 437-463.

Zimmerman, B. (2000). Attaining self-regulated learning: A social-cognitive perspective. In M. Boekaerts, P. Pintrich, & M. Zeidner (Eds.), *Handbook of self-regulation* (pp. 13–39). San Diego, CA: Academic Press.

Zull, J. E. (2011). *From Brain to Mind. Sterling.* VA: Stylus Publishing, LLC.