

Scientific Literacy: Resurrecting the Phoenix with Thinking Skills

Abstract

Prior research suggests that students' understanding of scientific concepts is pre-determined by their reasoning ability. Other efforts suggest that American students' scientific literacy is in decline. One difficulty Bybee (2009) acknowledges is that there are two divergent philosophical models of scientific literacy. The first describes the content knowledge and conceptual understanding that is desirable for future scientists. The second is an application of science to "real life" that is critical for every American citizen. In either case, we propose that the essential subordinate skill required for scientific literacy is *scientific thinking ability* as defined by Piaget (1964) and Lawson (2002). This article outlines the relation between students' scientific thinking ability and both their conceptual understanding and literacy. It also provides national norms for students in grades 10-12 using a measure of scientific thinking skills, the Classroom Test of Scientific Reasoning (CTSR). These norms can be used by educators when making curricular and policy decisions regarding student achievement.

Introduction

It has often been suggested that teaching should focus on conceptual understanding. In fact, Alan Greenspan (2002) described a conversion to a conceptual-based economy. Therefore, students need the prerequisite skills to be competitive. However, we find in Bybee (2009) that students are continuing to underperform

relative to our national expectations. As he points out, one of the areas of continuous or additional intervention is scientific literacy. It is also important to note that conceptual understanding has been linked to scientific thinking skills (BouJaoude, Salloum, & Abd-El-Khalick, 2004; Cracolice, Deming, & Ehlert, 2008); therefore, these skills ought not be neglected at the expense of scientific literacy. One difficulty Bybee acknowledges is that there are two divergent philosophical models of scientific literacy. The first describes the content knowledge and conceptual understanding that is desirable for future scientists. The second is an application of science to "real life" that is critical for every American citizen. In either case, we propose that the essential subordinate skill required for scientific literacy is *scientific thinking ability*. Scientific thinking includes the traditional reasoning abilities as described by Piaget (1964), as well as the hypothesis-testing skills described by Lawson (2002).

Conceptual understanding.

Herron (1975) described the relationship between scientific thinking skills and chemistry's conceptual difficulty. In essence, after looking at the traditional content and assessments of his course, he found that most of his teaching required students to have well-developed scientific thinking skills to be successful. Gabel (1999) agreed, suggesting that the vast number of student misconceptions regarding chemical concepts from the elementary school to the graduate level are due to the abstract nature of chemistry. Herron (1975) went on to suggest that chemistry instructors should challenge students to develop

these high-level scientific thinking skills in order to give them an opportunity to be successful in chemistry. Similarly, Coletta and Phillips (2005) found a positive correlation between scientific thinking skills and student achievement on the Force Concept Inventory (FCI) in physics.

Nurrenbern and Pickering (1987) found that students were more successful solving algorithmic problems (those which could be solved with a memorized set of procedures) than conceptual problems (those for which a memorized procedure was not available). This line of algorithmic versus conceptual problem solving research, including Nurrenbern (1979), Sawrey (1990), Nakhleh (1993), Sanger (2005), Sanger, Campbell, Felker, and Spencer (2007), and Sanger and Phelps (2007), has provided extremely insightful knowledge about the nature of students' problem solving abilities. As summarized in Cracolice et.al., (2008), the key findings were:

- 1) conceptual questions were significantly more difficult than algorithmic questions,
- 2) the difference in success rates on algorithmic and conceptual questions exists even for the high achieving students, and
- 3) the ability to assess students' problem solving ability is fundamentally dependent upon the types of questions posed.

However, Cracolice et.al., (2008) hypothesized that a cause of the gap between conceptual and algorithmic problem-solving ability is scientific thinking skills. Their research suggests

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that students with well-developed thinking skills are more successful at solving conceptual problems. Interestingly, on some of their algorithmic questions, there was no significant difference in achievement between students separated into groups with low-level or high-level scientific thinking skills. However, as the problems' conceptual difficulty increased, students with high-level scientific thinking skills were significantly more likely to solve them correctly than their low-level thinking skills counterparts.

High-stakes test designers are obviously getting the message (Drew, 2011). For example, the College Board (owner of the Advanced Placement exams) is completely redesigning its A.P. science exams. The biology exam will substantially reduce the breadth of testable information and will instead focus on conceptual understanding and problem solving. This change will challenge A.P. instructors to help students develop high-level scientific thinking skills in order to give the students an opportunity to be successful on these exams. As these changes lead to the modification of other assessments (e.g., state-level or federal), an even greater number of teachers will be impacted. Recently, the Department of Education suggested that teacher-training grants be linked to student achievement measures (Field, 2011). When this occurs, scientific thinking skills will become the essential focus of all consistently-successful teacher-training programs.

Student science achievement.

The National Assessment of Educational Progress (NCES, 2009) showed that 70% of 8th graders and 79% of 12th graders scored below proficient in science (Anderson, 2011). Even more astounding is that 37% of 8th graders and 40% of 12th graders scored below basic on this measure. These results are corroborated by the Program for International Student Assessment (PISA) data (Baldi, Jin, Skemer, Green, & Herget, 2007; Bybee, 2009). PISA has shown that scientific literacy is declining in the United States. In 2000, the U.S.

ranked 14th on PISA in science. In 2006, the U.S. ranked 21st. U.S. students not only struggle to learn science concepts, but also to develop scientific literacy. Even when specifically targeting scientific literacy, these scores have been difficult to revive. *In effect, our students' scientific literacy can be viewed as an educational Phoenix.*

Declining thinking skills.

In addition to student achievement declines, student thinking skills are declining as well. In a study of over 10,000 students over two decades, Shayer and colleagues have found that, "11- and 12-year-old children in year 7 are 'now on average between two and three years behind where they were 15 years ago', in terms of cognitive and conceptual development." (Crace, 2006).

Since students' scientific thinking skills development seems to predetermine their ability to solve conceptual problems (Cracolice, et al., 2008), teachers must be given the curriculum materials and the professional development (and must be willing) to reverse this trend. Improving thinking skills appears to be the most reasonable target when attempting to develop scientific literacy. After all, Bybee (2009) suggested that students with greater scientific literacy are more likely to be able to apply conceptual models to a variety of systems. Therefore, it is imperative that educational reform efforts immediately target inquiry interventions and thinking skills.

Scientific literacy.

Scientific literacy has been an important educational goal for decades. Hurd (1958) described the importance of scientific literacy this way, "Understanding science means knowing something about the procedures of theoretical inquiry and recognizing these procedures as the means by which the imagination of man and the laws of nature are focused on unsolved problems." (p. 16-17).

Bybee (2009) agreed, reminding us that PISA 2006 emphasized the importance of students' understanding of science as a process of inquiry and human knowledge. However, this understanding rests on the student's ability to generalize

well-defined scientific thinking skills to multiple contexts. These thinking skills, traditionally described as Piaget's (1964) formal reasoning skills and the hypothesis-testing skills described by Lawson (2002), are fundamental subordinate skills required for scientific literacy.

As Vygotsky (1987) argued, subordinate concepts are essential for higher concept development. Using Vygotsky's example, if a child is asked to describe what is in his living room, he may list objects such as sofas, recliners, coffee tables, etc. If an adult is asked to describe the contents of the same room, she may say "furniture." Since the adult has generalized each of the contents of the room to the more general concept of furniture, she needs only to use one concept to identify the contents of the room as a collective whole. The furniture concept is a higher concept to the subordinate concepts of sofa, recliner, etc. As her content knowledge becomes more sophisticated, it is logical to assume that the individual could represent her knowledge using fewer total concepts if the overall complexity of those concepts increased. In science, for example, students might be able to calculate density when given mass and volume information, but might struggle seeing the relation between that concept and the concept of stoichiometry. Another student may realize that each of those concepts just require proportional reasoning, or the equality of ratios. In this example, the second student has generalized the underlying proportional thinking skill to more contexts, making that skill more broadly useful to him or her. Therefore, before we can promote students' general scientific literacy we must enhance their scientific thinking skills.

Measuring Student Achievement

Thinking skills.

Anton Lawson (1978) developed the Classroom Test of Scientific Reasoning (CTSR) to accurately measure students' thinking skills, and also to inform teachers of instructional methods needed to effectively teach content material. In that article, Lawson also described the

validation of this assessment. Six experts in Piagetian research reviewed student responses and explanations to each demonstrated problem. This process gave the CTSR face validity, which indicated that the items on the assessment required concrete, early-formal, and formal thinking levels. To achieve statistical validity, four standard Piagetian interview tasks were given to 72 randomly selected students who also completed the CTSR. Student responses to two of the tasks were tallied and Lawson investigated the relationship between the CTSR and these tasks. A high correlation of 0.76 ($p < 0.001$) indicates that the assessment is strongly related to traditional Piagetian interview tasks. Overall, this assessment has been successful in measuring the same Piagetian thinking skills of the traditional interview methods with reasonable validity (Lawson, 1978).

After the development of this initial version of the CTSR, Lawson made numerous changes to the assessment when measuring students' thinking skills. Different versions of the test contain different questions, based on the specific study conducted by Lawson at the time. Since these early variations of the CTSR (e.g., 1978, 1983, & 1985), Lawson (2000) revised the test to contain thirteen multiple-choice items. To ensure the assessment of the desired skills, this exam was created using the technique of pairing two questions, a problem and a justification. This decision resolved many concerns regarding the amount of time to take the test as well as the desire for an objective scoring method. During the Lawson (2000) study, students were assigned to one of four levels (*Lawson's hypothesis-testing levels*; i.e., Level 0 = 0-3; Low Level 1 = 4-6; High Level 1 = 7-10; Level 2 = 11-13) for the purpose of comparing students' abilities to test various types of hypotheses.

However, to relate to the highest percentage of the teaching population, we assigned students to reasoning levels that correspond to Piagetian thinking stages (i.e., concrete = 0-4 and formal = 11-13), instead of using Lawson's hypothesis-testing levels (Lawson, 2000). We also included two additional categories, early

transitional (5-7) and late transitional (8-10), to more accurately reflect students' progression from concrete to formal thinking. These assignments were proposed to Lawson, who acknowledged that they were acceptable and "seem to work in terms of results matching theoretical predictions" (A.E. Lawson, personal communication, September 21, 2009).

Content knowledge.

Both state and national legislation have guided the establishment of the assessment system in Minnesota that has held schools and districts accountable for student learning since the 1990's (Minnesota State Legislature [MSL], 2007). The first set of assessments developed in this statewide system was the Minnesota Basic Skills Test (BST). These tests were designed to assess the skills in grades 8 and 10 mathematics and reading that are needed to succeed in the workforce, and were also the first statewide assessments required for graduation from high school (MSL, 2007). The Minnesota Comprehensive Assessments (MCAs) were then developed to assess student ability for statewide accountability in grades 3, 5, and 7

(MSL, 2007) and to aid in the decision-making process regarding classroom curriculum (Minnesota Department of Education [MDE], 2008). Shortly after No Child Left Behind (NCLB) was passed in 2001, the assessment system was modified, and required the states to create content standards for core subjects, assessment methods, and student proficiency levels regarding those standards. The legislation incorporated the evaluation of not only elementary and middle school students, but also high school students in statewide assessments. In the 2005 school year, students in grades 10 and 11 were included in the MCA Series II in both mathematics and reading (MSL, 2007). Data collected by the state from these assessments are included in the complex calculation of schools and districts meeting Adequate Yearly Progress (AYP) as well as the success of the students in Minnesota's standards based education system (MDE, 2008; MSL, 2007).

Achievement relationships.

Since the CTSR can be utilized to measure students' thinking skills levels from concrete to formal (i.e., mainly secondary students), it is appropriate to

Figure 1

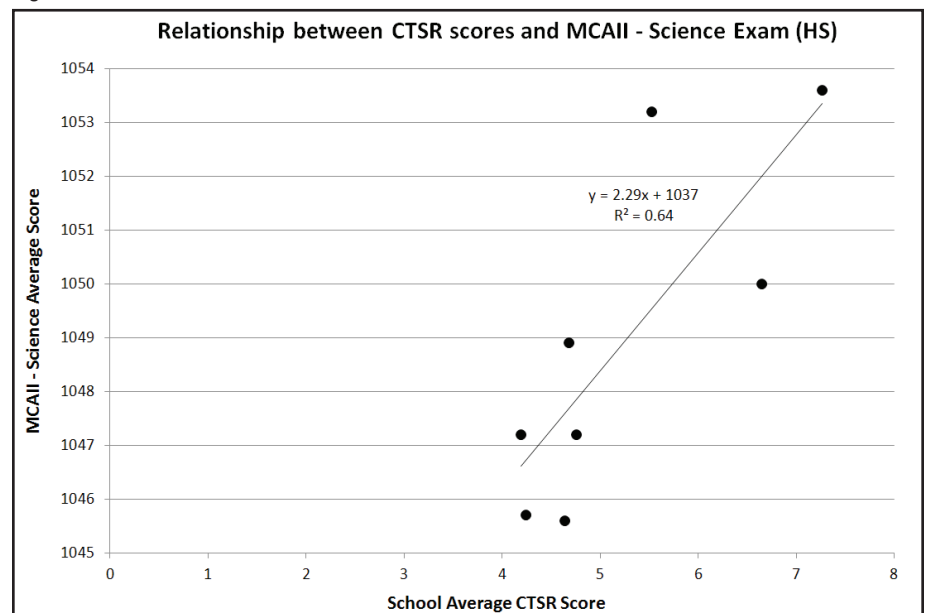


Figure 1: This figure illustrates the link between reasoning ability and relative science achievement. Each point represents one Minnesota school, comparing its average CTSR score to its average MCA II - Science score.

analyze schools' average scores on the CTSR compared to the MCA-II mathematics, reading, and science sections. Grade 10 students take the MCA-II reading and science sections and grade 11 students take the MCA-II mathematics

portion. Therefore, average MCA-II reading and science score can be plotted against the average CTSR score for students in grades 9 and 10 at a particular school. Similarly, the average MCA-II mathematics score can be compared to

the average CTSR score for students in grades 9, 10, and 11.

Figure 1 provides insight into the potential relation between a school's average CTSR score and its average MCAII-Science score. It is noteworthy to point out that we only included schools for which we had more than ten students' CTSR scores. These data are important because they corroborate Adey's (2004) results. These data also suggest that science teachers should consider utilizing a thinking skills measure that can provide comparisons in the United States. There is also a correlation between a school's average MCAII-Reading score and the school's average thinking skills score as measured by the CTSR (Figure 2).

For many educators, these data are not necessarily intuitive, as it is difficult for them to imagine a link between Reading and scientific thinking. However, these data also tend to corroborate Adey's (2004) findings. Figure 3 contains the same relationship between CTSR scores and MCAII-Math scores, but the correlation is lower than for the CTSR-Science or CTSR-English comparisons. The smaller correlation between the CTSR and MCAII-Math might provide insight regarding the level of the MCAII-Math questions, especially given the findings of Cracolice et al. (2008), Coletta and Phillips (2005), and BouJaoude et al. (2004) regarding success rates on algorithmic and conceptual questions.

These scientific thinking skills often go overlooked and/or unnoticed because many educators and educational policymakers continue to view student achievement in terms of socio-economic status (SES). Often, it seems that under-achieving schools are portrayed to be high-need schools and somehow that allows educational policymakers to deem their poor performance acceptable, or at the very least reasonable. It is troubling how pervasive this perception is because, as educators and educational policymakers, it is difficult to change a district's socio-economic status in a real student-centered time frame. More importantly, we found virtually no correlation between a school's average SES (as measured by the percent of students

Figure 2

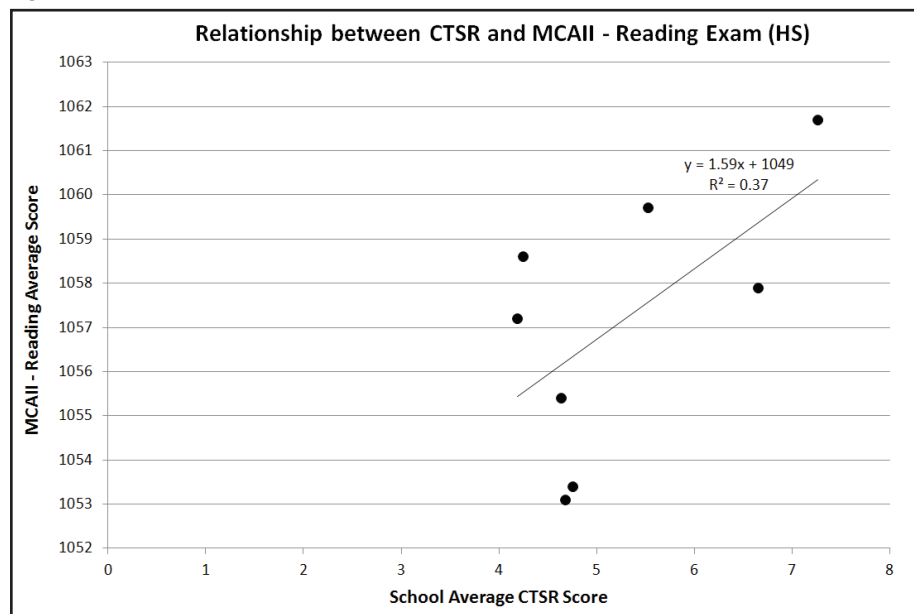


Figure 2: This figure illustrates the link between reasoning ability and relative reading achievement. Each point represents one Minnesota school, comparing its average CTSR score versus its average MCA II - Reading score.

Figure 3

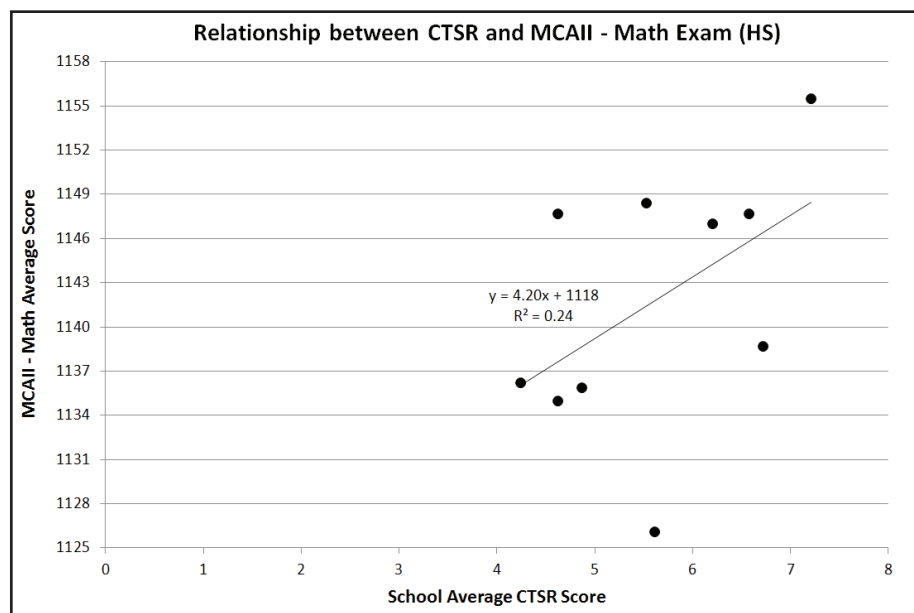


Figure 3: This figure illustrates the link between reasoning ability and relative math achievement. Each point represents one Minnesota school, comparing its average CTSR score to its average MCA II - Math score.

Figure 4

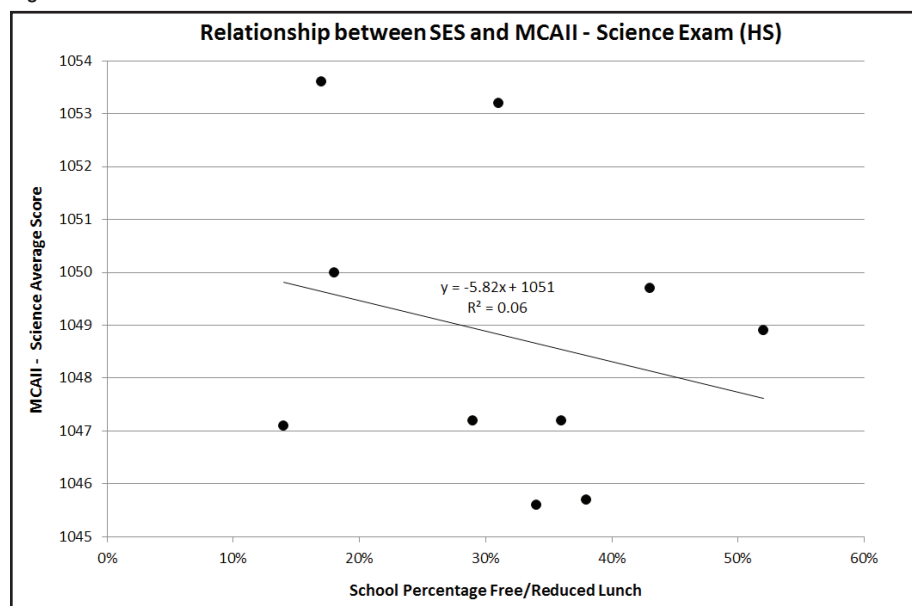


Figure 4: This figure illustrates the link between a school's average socio-economic status (as measured by the school's percent of students who qualify for free/reduced lunch) and that school's average MCA II - Science score. Each point represents one Minnesota school.

qualifying for Free/Reduced lunch) and its MCAII-Science scores (Figure 4). Therefore, a much more worthwhile option would be to implement specific thinking skills interventions that have a proven track record of success. Finally, it should be noted that the number of schools included in Figures 1 – 4 vary slightly due to the fact that a couple of the private schools did not take one or the other MCAA II tests.

Application to Concrete Practice

The results of the CTSR exam may be used to assess an individual's cognitive ability if educators both understand the nature of the thought processes required in different Piagetian stages and, more importantly, are willing to modify the course curriculum or teaching strategies to fit the proper developmental level (Lawson, 1992). Thus, if districts assess the thinking skills level of each particular class, they will be able to use such information to determine the most appropriate intervention for best possible gains. Instead of chasing the particular test(s) score(s) that decline(s) in a given year, targeting the underlying thinking skills should provide the greatest opportunity

for a district to systematically increase all scores simultaneously. A district-wide remediation effort in grades K-12 is necessary to provide students with their best opportunity to obtain these thinking skills. Without these skills, even the most determined students have little hope of succeeding in a college environment (Cracolice et al, 2008).

The good news is that there are materials available which have been shown to effectively target these thinking skills (Adey, Shayer, & Yates, 2001). In fact, students using these materials have outperformed traditional students by as much as 24% on thinking skills assessments. It is our belief that implementing a consistent thinking skills intervention across K-12 grade levels will not only allow students to outperform the average Minnesota student on MCA-II's, but also far outperform the national average on measures of scientific thinking skills such as the CTSR.

Using the CTSR as a diagnostic tool.

Growth curves for children's height use normative curves. Similarly, we used cumulative density plots to create

the normative curves for the CTSR score distributions. In essence, we are making growth curves for scientific thinking skills. These plots are based on the assumption that scores follow a normal or bell-shaped distribution (Caselle & Berger, 2002; Whitney, 1959). This assumption has been verified for our data. CTSR distributions appear approximately normal under various conditions (e.g. grade level, student age, gender, various teachers and schools). The strength of this assumption may not be robust against situations with too few observations where outliers may be present (not problematic here as scores range from 0 to 13). A large sample size was utilized in this study (n = 4486). These plots illustrate the expected distribution in CTSR scores under various circumstances. They can also be used to make comparisons in CTSR distributions across different situations as well. Only a mean and standard deviation are required to construct these plots.

The Frameworks for Inquiry Research Group has been given permission to distribute the assessment to educators (A.E. Lawson, personal communication, February 3, 2011). The form to request access to the CTSR may be viewed at the web address listed in Deming and O'Donnell (2011). The distribution of the CTSR and the continuation of this research will also allow the researchers to compare the results of the American education system over time, as long as test access is reasonably controlled.

Based on Piaget's Theory of Cognitive Development, students should begin to show transitions to formal reasoning between the ages of 11 and 12 (Piaget et al., 1966). However, when developing national normative curves for grades 7-12, it was found that more than 90% of the secondary students in the United States do not have formal thinking skills (O'Donnell, 2011). The normative curve for grades 10-12, collectively, is shown in Figure 5 along side a developmentally appropriate target goal. A description of the schools sampled, and their populations, is provided in Table 1. Epstein (2006) has suggested that, on average, only 34% of 17-18 year old students

Figure 5

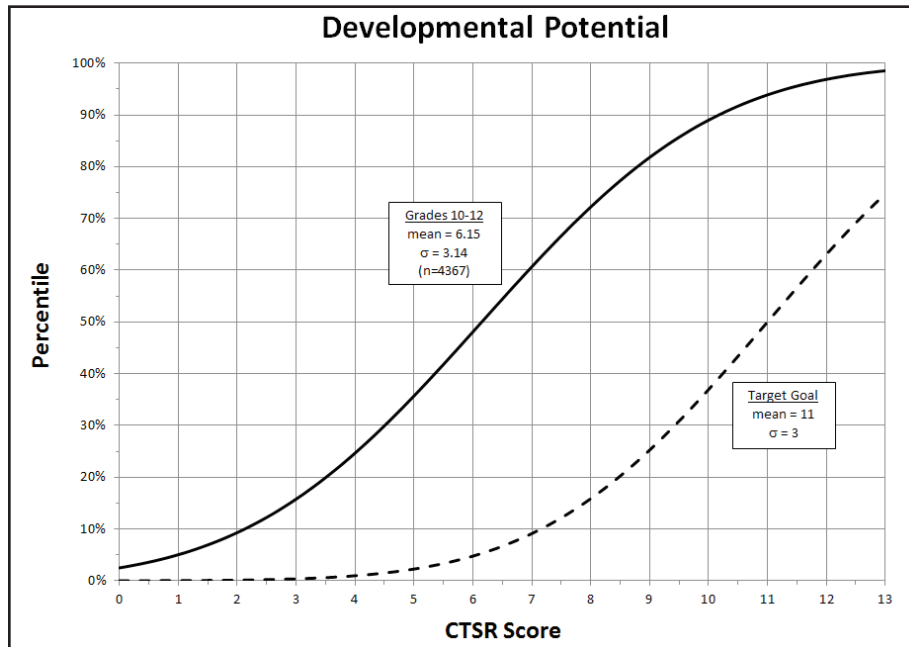


Figure 5: CTSR Target Goal - Shows the current national average for students in grades 10-12 on the CTSR and their theoretical developmental potential, based on the work of Inhelder and Piaget (1958), Piaget et al., (1966), Piaget (1972), as well as Epstein (2006).

acquire formal operational thinking before leaving high school. These data may help explain why 79% of 12th graders scored below proficient in science on NAEP (Anderson, 2011). In contrast, Piaget (2008) suggested that, “all normal subjects attain the stage of formal operations or structuring if not between 11–12 to 14–15 years, in any case between 15 and 20 years” (p. 45). His suggestion is clearly hypothetical, given the volume of studies that have found much smaller percentages of students attaining the formal operational level (Lawson, 1985). However, with systemic efforts to improve scientific thinking, it is reasonable to expect more students to develop formal thinking skills before leaving high school. Ideally, a normative curve similar to the target goal in Figure 5 would be observed. Instead of accepting Epstein’s (2006) percentage as a ceiling, we propose that 50% (or more) of students in grades 10-12 should be able to develop formal thinking skills by the time they leave school when appropriate intervention strategies are employed.

Setting Educational Policy

Notably, Bybee (2009) described the importance of inquiry in the PISA 2006. Utilizing inquiry strategies also aligns with the national standards for science (American Association for the Advancement of Science, 2009). However, the definition of inquiry often is ambiguous. For our purposes, Trowbridge and Bybee (1990) provide a useful 5E learning cycle inquiry model. When inquiry learning cycles are

utilized, students’ thinking skills development is significantly enhanced (e.g., Johnson & Lawson 1998; Musheno & Lawson, 1999). These data suggest that choices of curriculum and delivery methods--while teaching content--can have dramatic effects on student thinking skills development.

As previously discussed, Adey (2004) provided plenty of evidence that Cognitive Acceleration (CA) methods effectively enhance scientific thinking skills. These methods are drop-in interventions, where the focus is on thinking skills development rather than specific content. Those methods also dramatically improved student achievement in science, mathematics, and English. These intervention lessons were developed for students at ages 11+, but now CA materials are available for pre-K through adolescence in science, mathematics, and literacy (Adey et al., 2008). By using direct CA interventions, as well as 5E learning cycles when delivering content, the teacher ensures that students are engaged in the most likely process for enhancing student thinking skills development without sacrificing content.

Scientific thinking skills are important for developing the knowledge of future scientists or to develop the abilities of future citizens (Bybee, 2009). These skills may also predetermine a student’s success or failure on conceptual questions (e.g., Cracolice et al., 2008; Boujaoude et al., 2004; Coletta & Phillips, 2005). It is appropriate, then, to target these skills in an individual classroom. Additionally,

Table 1

n = 32 schools	Mean	Median	St. Dev.	Range
City Population	68,119	10,202	148,661.2	221 – 594,833
School Enrollment	809	573	604.1	34-2213
% Qualifying F-R Lunch	33%	25.5%	24%	8% - 98%

Table 1: Thirty-two schools from four states (IL, MN, MT, and WI) were included in this normative population, although not all students from any school were assessed. The percentage of students qualifying for free/reduced lunch in each school was used to estimate the percentage of families living at or below 185 percent of the national poverty level in this study, indicating socioeconomic status of the areas sampled.

we may find that developing these thinking skills results in the best of both worlds--we should be able to enhance students' content knowledge development while simultaneously developing students' ability to think scientifically. When this occurs, we will begin to see the educational Phoenix--scientific literacy--rise again.

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