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Is Adolescence a Critical Period for Learning Thinking Skills? A Case Study Investigating the Development of Formal Thinking Skills in a Short-Term Inquiry-Based Intervention Program

Forrest Towne
The University of Montana

IS ADOLESCENCE A CRITICAL PERIOD FOR LEARNING FORMAL THINKING SKILLS?

A CASE STUDY INVESTIGATING THE DEVELOPMENT OF FORMAL THINKING SKILLS IN A SHORT-TERM INQUIRY-BASED INTERVENTION PROGRAM

By

Forrest S. Towne

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Approved by:

Perry Brown, Associate Provost for Graduate Education
Graduate School

Mark S. Cracolice, Co-Chair
Department of Chemistry and Biochemistry

John Gerdes, Co-Chair
Department of Biomedical and Pharmaceutical Sciences

Edward Rosenberg
Department of Chemistry and Biochemistry

Sandy Ross
Department of Chemistry and Biochemistry

Allen Szalda-Petree
Department of Psychology

Towne, Forrest, Ph.D., July 2009 Chemistry

Is Adolescence a Critical Period for Learning Formal Thinking Skills?
A Case Study Investigating the Development of Formal Thinking Skills in a Short-Term Inquiry-Based Intervention Program

Co-Chairperson: Mark S. Cracolice

Co-Chairperson: John Gerdes

Current domestic and international comparative studies of student achievement in science are demonstrating that the U.S. needs to improve science education if it wants to remain competitive in the global economy. One of the causes of the poor performance of U.S. science education is the lack of students who have developed the formal thinking skills that are necessary to obtain scientific literacy. Previous studies have demonstrated that formal thinking skills can be taught to adolescents, however only 25% of incoming college freshman have these necessary skills. There is some evidence that adolescence (girls aged 11-13, boys aged 12-14) is a critical period where students must learn formal thinking skills, similar to the critical period that exists for young children learning languages. It is not known whether it is more difficult for students to learn formal thinking skills either prior to or following adolescence. The purpose of this quantitative case study is to determine whether adolescence is a critical period for students to learn formal thinking skills. The study also investigates whether a formal thinking skills focused program can improve students' intelligence.

In this study 32 students who had not developed any formal thinking skills, ranging in age from 10-16, underwent an intensive four-week, inquiry-based, formal thinking skill intervention program that focused on two formal thinking skills: (1) the ability to control and exclude variables and (2) the ability to manipulate ratios and proportionalities. The students undergoing the training were matched with control students by age, gender, formal thinking skill ability, and intelligence. The control group attended their traditional science course during the intervention periods.

The results of the study showed that the intervention program was successful in developing students' formal thinking skills. The pre-adolescents (males, age 10-11, females, age 10) were unable to learn formal thinking skills. The data indicated that there is not a significant difference between adolescents and post-adolescents (up to 16-years-old) ability to learn formal thinking skills. Both groups (adolescent and post-adolescent) showed improvement in their formal thinking skill ability after the intervention. The intervention also demonstrated evidence of improving students' intelligence scores.

This dissertation is dedicated to family. I am blessed.

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CHAPTER I

INTRODUCTION

This chapter provides the context to the research problem that was investigated. It also describes how and why it will address the problem, and it offers the research questions that it will seek to answer in addressing the problem.

Problem Background

Science education is in need of a new era of reform. It is not as obvious as it was in October 1957 when the Soviet Union launched Sputnik and the United States responded by pouring billions of dollars into science education (Yager, 2000). The U.S. no longer has a single competitor, an obvious goal, or a definite timeline. The reform efforts of the previous decade are not making any progress in obtaining their stated goals, and the U.S. is in danger of losing its competitive edge in the global economy (Bybee & Fuchs, 2006). Current domestic and international comparative studies of student achievement in science are demonstrating that the U.S. needs to improve science education.

The various studies of student achievement that have been conducted since 1965 have influenced educational policy and the direction of research in the United States. Guided by early studies such as the 1966 Coleman Report, which stressed the importance of family background, policy makers tended to concentrate on the plight of minority groups and improving equality of opportunity in schools rather than on other educational practices within schools.

Indicators of student achievement such as the National Assessment of Educational Progress (NAEP) seem to show that this approach was not effective as there was little change in science achievement over the period from 1973 to 1996 (Barton & Coley, 1998; Campbell, Reese, & Dossey, 1996).

The international comparative studies of curriculum coverage in mathematics and science carried out during the Trends in International Mathematics and Science Study (formerly known as the Third International Mathematics and Science Study, TIMSS) from 1994 to 1995 suggest that the content and organization of mathematics and science curricula and how these subjects are presented in the classroom might influence student achievement (Mullis, Martin, Beaton, Gonzales, Kelly, & Smith, 1998). Results indicated that a lack of focus in the curricula and the extremely variable pattern of school offerings contribute to the relatively low U.S. achievement levels compared to the other countries in the study. The high diversity of ethnicity in the United States does not appear to have been an important factor influencing the nation's ranking in TIMSS. Scores for the white only students at the end of secondary school place the United States in the lowest one-third of all the participating countries, with the performance of minority groups having little effect on the country's overall position in this study. High school physics students, the country's most highly selected and potentially top achievers, were in fact amongst the lowest performers of 17 participating countries (Mullis, Martin, Beaton, Gonzales, Kelly, & Smith, 1998).

In response to the TIMSS data indicating that a focused curriculum is beneficial and that the U.S. is falling behind in scientific literacy internationally, as well as reports such as *A Nation at Risk* (National Commission on Excellence in Education, 1983), the science education community requested that the National Research Council (NRC) develop a set of science education standards for all American students (NRC, 1996). The NRC released the *National Science Education Standards* (NSES) in 1996. The stated purpose of the NSES was to enable the nation to achieve the national goal of scientific literacy for every student in the country in the 21st century.

The *Standards* outline what students need to know, understand, and must do to be scientifically literate at different grade levels (NRC, 1996). The document also addresses the need for change through out America's entire school system. A prominent feature of the *Standards* is a focus on inquiry (NRC, 2000). They emphasize that inquiry is central to science learning and that teachers must use this pedagogical technique to achieve the goals of the NSES. The *Standards* describe inquiry in education as:

> A multifaceted activity that involves making observations; posing questions; examining books and other sources of information to see what is already known; planning investigations; reviewing what is already known in light of experimental evidence; using tools to gather, analyze, and interpret data; proposing answers, explanations, and predictions; and communicating the results. Inquiry requires identification of assumptions, use of critical and logical thinking, and consideration of alternative explanations. (p. 23)

Inquiry instruction contrasts with expository or direct instruction in that students must construct their understanding of concepts in an environment where the instructor acts as a facilitator as opposed to a lecturer who gives the students the definitions and examples of the concepts before they verify, in the laboratory, that the concepts were defined correctly.

However, the *Standards* do not appear to have been successful in enhancing the achievement of the majority of U.S. students. Since the NSES have been released student achievement in science for eighth and twelfth graders has either remained constant or decreased (Grigg, Lauko, & Brockway, 2006). Only a little over half of the eighth and twelfth graders that participated in the NAEP study in 2005 had at least a basic understanding of science, a level that is defined as only a partial mastery of knowledge and skills that are fundamental for proficient work at a student's respective grade. At the eighth grade only 29% of the students performed at or above the proficient level, which is the national standard and is representative of a student having competency over challenging subject matter and indicates they are well prepared for the next level of schooling. At the twelfth grade only 18% are at or above the proficient level in science.

The results of the Organization for Economic Cooperation and Development's Program for International Student Assessment (PISA) show lower than average performance in mathematics and science for 15-year-old U.S. students, when compared with participants from 32 countries (NCES on-line, 2007). PISA is a relatively new system of international assessment that focuses on literacy skills in reading, mathematics and science. The purpose of PISA is to represent the overall yield of learning that 15 year olds have acquired as they near the end of mandatory schooling. The most recent TIMSS data (Gonzales, Guzmán, Partelow, Pahlke, Jocelyn, Kastberg, & Willams, 2004), collected in 2003, also show the U.S. performing at either average or below average when compared to the other 45 countries on the TIMSS assessment.

The low ranking of the U.S. in international comparative studies such as TIMSS and PISA indicate that it is time to take a closer look at what is occurring in mathematics and science classrooms. Over a decade has passed since the *Standards* have been released, and science achievement is not improving in America. Is inquiry-oriented instruction failing to improve student achievement? The research and evaluation of inquiry instruction gives mixed results (Lawson, Abraham, & Renner, 1989; Mayer, 2004) and while most in the science education community believe inquiry instruction is superior to the traditional expository method, there is a healthy debate on the most effective pedagogical approach (Sweller, Kirschner, & Clark, 2007).

One explanation for the failure of the NSES and inquiry-oriented instruction in improving science achievement in this country may be that a mismatch frequently occurs between intellectual ability and the cognitive demand of the inquiry-based curriculum materials for the many students who are still operating at the concrete level of thinking in secondary school (Zahor, 2004). Therefore, inquiry instruction, with a lack of guidance by the instructor, may be too cognitively demanding for many students as an instructional method and consequently, it is not effective in developing students' conceptual knowledge. An unguided inquiry investigation requires the manipulation of formulas, the design of scientific experiments, and making the necessary connections between concrete experimental data and abstract scientific theory, all of which are formal thinking skills. From this perspective, the study of science becomes more than just a challenge to a student whose thinking has not yet reached the formal operational level of cognitive development. They simply do not have the cognitive ability to succeed. Achievement in science, and in other subjects, is likely to be related to cognitive development, and enhancement of cognitive development would therefore improve students' science achievement as well as the effectiveness of inquiry instruction.

Science curriculum materials developed at King's College in London focus specifically on developing students' cognitive ability (Adey & Shayer, 1994; Shayer & Adey, 1981). The success of the curriculum, called Cognitive Acceleration through Science Education (CASE), in improving cognitive development has been demonstrated convincingly in England (Adey & Shayer, 1990; Adey & Shayer, 2002; Shayer, 1999; Shayer & Adey, 1992), in Pakistan (Iqbal & Shayer, 2000), and in Australia (Endler, 1998; Endler & Bond, 2001). The British CASE research demonstrated a positive relationship between the results of the General Certificate of Secondary Education (the UK equivalent of the SAT) and cognitive tests (Adey & Shayer, 1994, 2002), suggesting an association between cognitive development and student achievement. The success of CASE is attributed to its strategies that actively promote the development of formal thinking skills in students (Adey & Shayer, 1990, 1994). Adey and Shayer (1994) reported increased cognitive development from pre-intervention students of every cognitive ability. They found that the students who made the greatest gains were not restricted to those who had much ground to make up, or to those who were more able and therefore perhaps more ready to move on to formal thinking, a finding confirmed by Endler & Bond (2001). Shayer (1999) reported evidence of the long-term effect of CASE on students' school results in science, mathematics and English in the UK. This trend was supported by the Australian CASE study, in spite of using different indicators of student achievement (Endler & Bond, 2001).

Despite the success of the CASE program educators in the U.S. have not focused upon developing students' formal thinking skills. Only one study has been reported which evaluated the effectiveness of CASE and focused on developing students' formal thinking skills in the U.S. (Endler & Bond, 2008).

Studies that have assessed students' formal thinking skills have shown consistently that only about 25% of incoming freshman students at the university level have the ability to use formal reasoning skills to solve problems requiring those abilities (Bitner, 1991; Cracolice, Deming, & Ehlert, 2008; Lawson & Renner, 1974; Niaz & Lawson, 1985; Valanides, 1999). It has also been demonstrated that many scientific concepts cannot be conceptually understood without formal thinking skills (Cracolice, Deming, & Ehlert, 2008, Lawson & Renner, 1975). If students have not developed formal reasoning skills it does not matter how the material they are to learn is presented to them; they cannot conceptually understand many scientific concepts at the formal operational level unless they have developed those abilities. One of the probable causes of the failure of the American education system to improve science achievement is the lack of attention on developing students' formal thinking skills.

While the CASE program showed the potential of improving students cognitive ability by focusing on specifically developing their formal thinking skills, it has raised several questions. Although it appears that a formal thinking skills focused instructional curriculum is effective regardless of the student's initial cognitive ability, it only hints at an age effect. The British CASE program was only effective at specific ages. The data appeared to indicate that subjects who had not reached adolescence or who were past adolescence did not develop their formal thinking skills. This raises the question of whether adolescence is a critical period for developing formal thinking skills. Is it too late for students who are past adolescence to learn formal thinking skills? Are those students who have not fully developed their formal thinking skills post-adolescence (75% of incoming college students) condemned to never be successful in the sciences or even in other disciplines? Is it too early to teach pre-adolescent students important formal thinking skills such as the importance of identifying and controlling variables in an experiment because they are not cognitively ready to learn such concepts?

Another important question only hinted at but left unanswered by the CASE research was its effect on student intelligence. Will a formal thinking skills focused instructional curriculum improve students' scores on measures of intelligence? Answering this question will also answer the larger question of whether intelligence is plastic. Is it possible to improve students' intelligence by using an effective research based instruction method or is intelligence primarily fixed?

Problem Statement

The primary goal of this study is to determine whether adolescence is a critical time period when students must develop formal thinking skills. Can students who have not reached pubescence (girls 10 years old and younger, boys 11 years old and younger) learn formal thinking skills? Can students who are past pubescence (girls 14 years and older, boys 15 years and older) learn formal thinking skills? The study will also investigate whether an intensive short-term, inquiry-based, formal thinking skills focused intervention program is effective at improving students' formal thinking skills and overall intelligence. The study will also help to begin answering the question of whether intelligence can be improved with instruction as well as potentially refocus some of the science education community's attention toward developing students thinking skills as opposed to just content knowledge.

In this investigation students who have not developed any formal thinking skills ranging in age from 10 to 16 will undergo an intensive four-week inquiry-based formal thinking skills focused intervention that will concentrate on two specific formal thinking skills: (1) the ability to control and exclude variables and (2) the ability to manipulate ratios and proportionalities.

Significance of the Study

Many educators and educational experts agree that the central goal or purpose of education is to develop students' ability to think. When students are able to reason at a high level it often has a positive influence on their quality of life, their ability to contribute to a democratic society, their potential to achieve success in academia, and their capability to learn independently and obtain their life goals. However, our science education goals are more oriented toward specific content knowledge requirements. This requires instructors to prepare their students to answer questions that require factual or declarative knowledge instead of the ability to problem solve or develop their abilities to reason and think. Our science education goals do not match the most important goals of education. If it is determined that focusing upon developing students' thinking skills in science education can improve students' intelligence; therefore providing evidence that intelligence can be modified by a particular pedagogy, a stronger argument can be made and more attention brought to the need to change the focus of science education in the U.S. to one with more of a thinking skills emphasis. This study will seek to ascertain whether that argument should be made.

Research Questions

This study seeks to answer the following three research questions.

1. Will students who are taught to develop their formal thinking skills in eight science class replacement intervention sessions achieve significantly greater scores on measures of formal thinking skills than students of the same age who do not undergo the intervention?
    a. Will the scores on the control and exclusion of variables and proportionality reasoning skills targeted in the intervention sessions be greater for the treatment students when they are compared to the control students by age?
    b. Will the scores on the formal thinking skills not specifically targeted in the intervention sessions be greater for the treatment students when they are compared to the control students by age?

2. Will some age levels have more success learning formal thinking skills than other age groups?
    a. Will adolescent boys aged 12-14 achieve greater scores on measures of formal thinking skills than pre-adolescent boys aged 10-11 and post-adolescent boys aged 15-16?
    b. Will adolescent girls aged 11-13 achieve greater scores on measures of formal thinking skills than pre-adolescent girls at an age of 10 and post-adolescent girls aged 14-16?
3. Will students who are taught to develop their formal thinking skills in eight science class replacement intervention sessions achieve significantly greater scores on measures of intelligence than students of the same age who do not undergo the training?

Central Research Hypothesis

The theoretical framework from which the hypothesis, research questions, and research study are derived is described in Chapter II. The theory, constructivism, specifically Piaget's genetic epistemology, asserts that intelligence develops in four stages according to physical maturation and social interaction. Based upon the evidence presented in the problem background and the literature review in Chapter II it is posited that the final stage of intellectual development must occur during the onset of adolescence for an individual to develop full formal thinking and therefore:

An intervention program, which attempts to develop students' formal thinking skills by teaching those skills directly, using inquiry-based instruction, will allow adolescents (girls aged 11-13, boys aged 12-14) to learn and use those skills. Due to the neurological maturation that occurs during adolescence, pre- and post-adolescents are unable to learn formal thinking skills.

Based upon this hypothesis, the following outcome is predicted for the first research question.

> Students who are taught to develop their formal thinking skills in eight science class replacement intervention sessions will achieve significantly greater scores on measures of formal thinking skills than students of the same age who do not undergo the intervention.
>
> a. Scores on the control and exclusion of variables and proportionality reasoning skills targeted in the intervention sessions will be greater for the treatment students when they are compared to the control students by age.
>
> b. Scores on the formal thinking skills not specifically targeted in the intervention sessions will be greater for the treatment students when they are compared to the control students by age.

Based upon this hypothesis, the following outcome is predicted for the second research question.

Some age levels have more success learning formal thinking skills than other age groups. Specifically:

a. Adolescent boys aged 12-14 will achieve greater scores on measures of formal thinking skills than pre-adolescent boys aged 10-11 and post-adolescent boys aged 15-16.
b. Adolescent girls aged 11-13 will achieve greater scores on measures of formal thinking skills than pre-adolescent girls at an age of 10 and post-adolescent girls aged 14-16.

Based upon this hypothesis, the following outcome is predicted for the third research question.

Students who are taught to develop their formal thinking skills in eight science class replacement intervention sessions will achieve significantly greater scores on measures of intelligence than students of the same age who do not undergo the training.

CHAPTER II

LITERATURE REVIEW

"The purpose which runs through and strengthens all other educational purposes–the common thread of education–is the development of the ability to think" (Educational Policies Commission, 1961, p. 12). "Education…should help students to develop the understandings and habits of mind they need to…think for themselves" (AAAS, 1990, p. xiii). It is an educator's responsibility, regardless of their discipline, to attempt to develop students' ability to think; that is, to improve students' thinking skills. Several questions arise for an educator seeking to accomplish this goal: (1) What are thinking skills? (2) Why are thinking skills important? (3) Can thinking skills be taught? (4) How can thinking skills be taught? This literature review will investigate and critically analyze the research in developmental psychology and science education that attempts to address each of these questions.

Theoretical Framework – Constructivism

Before attempting to address these questions it is important to first delineate a prominent theory of how students learn. The underlying theory guiding the treatment design of this study is the constructivist learning theory based largely on the cognitive and developmental perspectives of Jean Piaget and the cultural emphases of Lev Vygotsky.

Piaget's Genetic Epistemology

In the early part of the twentieth century, the prevailing view of the child's cognitive activity was that it was the same as that of adults, merely becoming more efficient with use. Piaget challenged this perspective by his claim that children's thinking passes through a series of developmental stages that progressively show greater sophistication. His idea that a child thinks and learns in qualitatively different ways during particular developmental periods was revolutionary at that time. In their book *The Growth of Logical Thinking from Childhood to Adolescence* (GLT), Inhelder and Piaget (1958) outlined the transition of children's thinking from the concrete operational period of childhood to the formal operational period of adolescence. The thinking of a child in the concrete operational stage is characterized by inductive reasoning limited by personal experience in the concrete world, whereas the formal operational adolescent can think effectively in the abstract mode. Piaget concluded that formal thinkers can dissociate general ideas or concepts from the contexts in which they were learned and therefore specific concrete cues are not necessary to trigger the recall and use of these general principles. There is some evidence that contradicts this claim and provides evidence that formal thinking is context specific (Lawson, 1985). Formal thinkers are also able to intellectually manipulate concepts by integrating them into universal generalizations or by taking these generalizations back to their first principles. Furthermore, formal operational thinking is hypothetico-deductive; the student is able to conceive new ideas, concepts, hypotheses or principles, explore their implications and then test for their validity.

Piaget and Inhelder developed a clinical method to discover how the thought processes of the adolescent differ from those of a child. Typically, a number of children or adolescents were presented with an apparatus such as a pendulum or a balance and were required to explain how it operates. The subject was essentially being asked to behave as a scientist by designing a series of experiments, observing the results, and drawing logical conclusions.

Using the clinical method, Piaget and Inhelder were able to present adolescents with investigations that were related to the complex thinking that underlies the mastery of many scientific concepts. The various chapters of *GLT* illustrate the adolescent development of the major reasoning patterns required for effective thinking in the biological and physical sciences as well as other academic disciplines.

Inhelder (2001) had previously observed that adolescent mental operations differ from those of younger children. She deduced that adolescent thought reaches a higher degree of equilibrium, becoming more flexible and effective, so that adolescents are able to deal with complex reasoning problems. Adolescents develop the ability to imagine the many possibilities inherent in a situation, comprehending hypothetical propositions and compensating mentally for transformations in reality.

Piaget's earlier theoretical work (1953) resulted in two logical models, the 16 binary operations and the INRC transformations, which are used to define the structure of formal operations. The 16 binary operations model situations involving two factors, for example pendulum length and weight, where each factor has two values (e.g., long/short or heavy/light). An illustration of the binary operation known as complete affirmation would be the observation that a pendulum of heavy or light mass can swing with either a low or high frequency, with the conclusion that weight makes no difference to the frequency of oscillation. If the child being interviewed also concluded from other observations that length determines the frequency of oscillation, then another of the 16 binary operations, reciprocal implication, would have been demonstrated. The attainment of each of the 16 binary operations is determined by whether the adolescent is able to derive the proper logical relations from among the factors involved in the experiment.

Following his analysis of functions, Piaget (1953) formulated a second model of adolescent development, known as the INRC four-group, that describes how adolescent reasoning is used to manipulate the conclusions from any experiment. The INRC four- group specifies four cognitive transformations that adolescents can use to manipulate functions, namely identity (I), negation (N), reciprocity (R) and correlativity (C). N is the inverse operation of the four-group; N and R are both forms of reversibility or ways of reversing the operations of thought. I is an identity operator, which, when applied to a function, leaves the function unchanged. C changes the conjunction operation to disjunction, and vice versa, but leaves everything else unchanged (Ginsburg & Opper, 1988).

The equilibrium of a simple beam balance provides a useful illustration of the INRC 4-group (Baldwin, 1967). If adding an additional weight to one side disturbs the equilibrium of a balance with equal weights at equal distances, the equilibrium can be regained in several ways. First, the added weight could be removed in the same way in that it was added to restore the starting position. Another possibility would be to add an identical weight to the lighter side. A third way involves moving the heavier weights along the beam closer to the pivot than the weights on the lighter side. The last two strategies would restore the equilibrium, but not the starting arrangement.

An adolescent who has attained formal operational thinking would correctly conclude from experimenting with a balance that both weight and distance from the fulcrum are variables that affect equilibrium, and so determine whether balance is achieved (Inhelder & Piaget, 1958). The nature of the inverse relationship between the two variables (distance and weight) would be revealed if the adolescent discovered that a small weight combined with a great distance is equivalent to a large weight combined with a small distance. If the child simultaneously increased both the weight and the distance on one of the arms of the balance during the experiment, and discovered that this had no effect on equilibrium, then the child would have shown understanding of I (the identity operator that leaves a function unchanged). Reducing the distance while increasing the weight, diminishing the weight while increasing the distance, or diminishing both, would demonstrate N (the inverse operation). In discovering that a change in weight can be compensated by a change in distance, the child would have shown understanding of R (reciprocity).

Piaget argued that the period of formal operations could be subdivided into an early sub-stage, commencing at about 11 years, and a later stage, commencing at about 14 years. Inhelder and Piaget (1958, p. 347) said:

> [A]fter a phase of development (11-12 to 13-14 years) the preadolescent comes to handle certain formal operations (implication, exclusion, *etc*.) successfully, but he is not able to set up an exhaustive method of proof. But the 14-15 year old adolescent does succeed in setting up proofs (moreover, spontaneously, for it is in this area that academic verbalism is least evident). He systematically uses methods of control which require the combinatorial system—*i.e.*, he varies a single factor at a time and excludes the others ("all other things being equal"), *etc*.

Piaget is not very explicit about how the final stage of formal operations is attained. He suggested that neurological change occurs around the age of puberty and that this provides the physical basis for the transition from concrete to formal operations. Piaget also observed a facilitative social environment where the child has the opportunity to experiment with objects and thus initiate internal cognitive reorganization, as crucial to the development of formal structure.

Formal Operational Thinking

There was strong interest among educators in Piaget's ideas in the 1960s and early 1970s; several replications were performed of Inhelder's and Piaget's original research on the acquisition of formal operational thinking.

Lovell (1961) tested a sample of 200 subjects (eight years to adult) with 10 of the problems described in *GLT* that generally substantiated the work of Inhelder and Piaget. Jackson (1965) also performed a supportive replication with 48 children of normal intelligence aged five to 15 years and 40 subnormal children aged seven to 15 years. His research demonstrated consistency of achievement across six tasks from *GLT* and was also successful in estimating the proportion of his sample that had reached each Piagetian sub-stage of cognitive development. He found no formal thinkers in the subnormal group.

Lovell and Shields (1967) found that of 50-gifted 8- to 10- year-old children, only 10% were at the level of formal operations in spite of their records of giftedness. This study suggested that there is a maturational aspect of developing formal reasoning.

Lawson and Blake (1976) investigated the performance of 68 high school biology students on three of Inhelder's tasks. The students ranged in age from 14 years seven months to 17 years 10 months, with a mean age of 15.5 years. Lawson and Blake concluded that 15% of the group was at the early concrete stage of cognitive development, 42% were mature concrete thinkers, 35% were at the early formal stage and only 8% of the students were operating at the mature formal level. This study raised the concern that there might be fewer formal thinkers than previously expected among high school students. The implication drawn from the work of Lawson and Blake was that children restricted to concrete operational thinking are generally unable to develop formal concepts from standard lecture type high school classes and that they need concrete examples to work with before reflective abstraction can take place. In a later study with 507 students aged between 11.5 and 20 years, Lawson, Karplus and Adi (1978) administered a paper and pencil test of ability in proportions, probability, correlations and propositional logic. They concluded that there was an increase with age for performance on items requiring the formal schemata but that this was not as clearly demonstrated for what was described as propositional logic items.

A number of studies have been carried out to investigate the distribution of Piagetian stages in populations of school children. In the most comprehensive of these, Shayer, Küchemann and Wylam (1976) calculated the proportion of children showing early and mature concrete operational thinking and early and mature formal operational thinking in a representative sample of more than 10,000 children between the ages of 9 and 14 in Great Britain. They used demonstrated class-tasks derived from Inhelder's individual interview situations. Shayer et al. (1976) concluded that most children in early adolescence showed rapid development in concrete thinking, but only one fifth showed the further development of formal operational thought.

In a further study of 1,200 15- to 16-year-olds, Shayer and Wylam (1978) found no increase in the proportion of students showing formal operational thinking beyond the age of 15 years. There was no increase for girls after the age of 14 whereas the boys continued to develop for an additional year. Although Inhelder and Piaget gave some general indication of the ages at which their sample of children was capable of formal operational thought (see Bond, 2001, p. 75 Table 4.1), it would not be reasonable to expect to replicate their findings in populations of children from vastly different settings. Indeed, Piaget (1972) later claimed that their research had been conducted with a somewhat privileged population and that generalizations to all subjects cannot be made from their conclusions. The results of Shayer, Küchemann and Wylam (1976) were from children in comprehensive schools, selected to obtain a strictly representative sample of the British population. They also showed that if a selective school population is sampled by testing children from grammar schools and private schools only, formal operational thinking is detected from the beginning of secondary schooling (more in line with the general view derived from *GLT*).

Despite its strengths, many researchers have criticized Piaget's theory. How well has Piaget's theory held up in the face of more contemporary research? The most valid critique of Piaget's theory is the lack of evidence supporting his mental functioning model, the theory that describes how students transition from one stage to the next. In Case's (1987) review of the primary neo-Piagetian theories, he finds that the five most prominent neo-Piagetian theories (Pascual-Leone, Fischer, Halford, Case, Demetriou) retain Piaget's universal theories of cognitive development, namely that there are different stages of cognitive development. Where the theories differ is in their description of how individuals transition from one stage to another. The reason for this is due both to the vagueness of Piaget's explanation of structural transformation and to the neo-Piagetian researchers' choice of a theoretical approach to use in extending Piaget's transformation model, with the majority of the researchers assuming that thinking is information processing (Driscoll, 2005).

Halford (1989), in reviewing the research that has investigated cognitive development from a Piagetian perspective over the first twenty-five years since Piaget proposed it (1963-1988), stated that there is no evidence clearly confirming the existence of Piaget's cognitive structures in explicit form. The research that he investigated did support Piaget's general cognitive development theory. He indicates that there is an overwhelming amount of evidence over the aforementioned twenty-five year period that supports the theory that individuals transition through cognitive stages. Halford suggests that researchers need to begin testing alternative theories that will reveal how individuals transition through stages due to the lack of evidence supporting Piaget's mental functioning model.

Vygotsky's Social Construction of Reasoning

Increased interest in the sociocultural aspects of cognitive development has prompted researchers to explore how language, social interactions, and contexts contribute to cognitive development. This increased awareness has been guided by Vygotsky's theory that social relationships underlie all higher mental functions. Vygotsky proposed that a child will internalize an experience only after transformational processes take place between people, interpsychologically, before being directed inward, intrapsychologically (Vygotsky, 1988). An example of this transformation occurs when dialogue with others becomes internalized to become part of an individual's inner thoughts (Wertsch, 1985). Vygotsky also claimed that one could only understand the higher mental functioning of an individual by examining the preceding sociocultural context (Vygotsky, 1978).

Vygotsky viewed teaching and learning as social processes and his zone of proximal development (ZPD) illustrated how teaching and learning interact. The zone of proximal development is defined as the distance between what an individual can accomplish alone and what is possible when assistance is given by a more capable collaborator (Vygotsky, 1978). The method used to determine this social component of learning begins with the psychologist administering a standard test, such as the Binet intelligence test, from which the mental age of the subject is estimated. The psychologist, who discusses the problems and gives various hints on their completion, then takes the child through some of the easier incorrect items. The child is now able to solve more of the test items with the assistance of the psychologist, and so a new mental age can be calculated. The difference between the two test scores (with and without the mediation of the psychologist) represents the ZPD of the child (Shayer, 2003).

In the classroom setting, a more advanced peer might assist the development of a child by prompting, modeling, explaining, asking leading questions, discussing ideas, providing encouragement, or keeping the attention on the learning context (Carter & Jones, 1994; Jones & Carter, 1994). Contexts for such assistance might include peer tutoring, cooperative learning, and sibling relationships (Forman & Cazen, 1985). Furthermore, Vygotsky claimed that within the zone of proximal development, language and other social interactions between individuals enhance learning.

Signs and tools as mediators of knowledge also play an important part in Vygotskian theory (Driscoll, 2005; Vygotsky, 1978). Signs can include internalized ideas, beliefs and concepts; as well as symbols such as the alphabet, language and numbers that are both externally and internally oriented. Tools, such as the memory aids created by an individual to provide internal cues to prior knowledge, are also seen to be externally and internally oriented. Vygotsky's argued that a child's understanding of the function of a tool comes from involvement in culturally organized activities in which the tool is involved, rather than from unaided exploration of the tool itself. Teachers provide students with a special set of manipulative tools in science lessons, such as microscopes and measuring instruments. However, little is known about how the use of these tools directly contributes to students' understanding of scientific concepts.

Although Vygotsky's theories have become increasingly popular, there is little research yet to support or refute the applications of these theories into teaching practice. Shayer (2003) argued that if one wants to see the specifics of what is present in various children's ZPDs, and if evidence is required that partially achieved schemes are in children's minds before they achieve them, it is in the work of Piaget, rather than Vygotsky, that this evidence will be found recorded in fascinating detail.

Constructivism

The constructivist theory of knowledge is a logical outgrowth of Jean Piaget's theory of intellectual development and Vygotsky's social construction of reasoning as well as the influences of David Ausubel (Ausubel, Novak, & Hanesian, 1978), Ernst von Glaserfeld, and Thomas Kuhn (1970) among others.

George Bodner, who introduced constructivism to many in the chemical education community, summarized the constructivist model in a single statement, "knowledge is constructed in the mind of the learner" (Bodner, 1986, p. 873). von Glaserfeld (1984) describes constructivism in more detail:

> …learners construct understanding. They do not simply mirror and reflect what they are told or what they read. Learners look for meaning and will try to find regularity and order in the events of the world even in the absence of full or complete information. (p. 30)

Constructivism theorists often contrast their ideas with the epistemological assumptions of the objectivist tradition. Both the behavioral and the cognitive information-processing theories of learning emerged from the objectivist tradition. Objectivism is the view that knowledge of the world comes about through an individual's experience of it. As this experience grows broader and deeper, knowledge is represented in the individual's mind as an ever-closer approximation of how the world really is. Knowledge is thought to exist independently of learners, and learning consists of transferring that knowledge from outside to within the learner. This view of knowledge, which is often referred to as the traditional view of knowledge due to it being the primary theoretical base for instruction during the last half of the twentieth century, is what educators use to defend lecturing as an effective instructional technique. They reason that if knowledge is truly independent then knowledge can be transferred directly from the mind of the lecturer to the mind of the students. The traditional view of knowledge views the mind as a black box; we can accurately judge what goes in (stimulus) and what comes out (response), but we can only guess about what is happening inside the box (Bodner, 1986).

In contrast to the objectivist view, constructivist theory rests on the assumption that learners construct knowledge as they attempt to make sense of their experiences. Learners are not empty vessels waiting to be filled, but rather active organisms seeking meaning. Regardless of what is being learned, constructive processes operate and learners form, elaborate, and test candidate mental structures until a satisfactory one emerges (Perkins, 1991). New conflicting experiences cause perturbations in these structures, so they must be constructed anew in order to make sense of the new information.

What constructivists argue strongly, however, is that knowledge constructions do not necessarily bear any correspondence to external reality. An individual's mental representation does not have to reflect the world as it really is, to be useful and viable. This does not necessarily mean that all constructions are equally viable. There are limits to what sense learners can make of their environment and their experience. Limits are imposed by human biological characteristics as well as by what is possible in reality. Moreover, learners must have some reliable and systematic way to test their observations and the sense they are making of the world around them (Matthews, 2003).

Summary

A prominent group of cognitive scientists has questioned the central claims of constructivism, saying that they are either misleading or contradict known findings (Anderson, Reder, & Simon, 2000; Hau Liu & Matthews, 2005; Holloway, 1999). There is a need for more empirical research to be done to evaluate its claims and implications for teaching and learning. One of the strongest validations of constructivism is that the learning theory matches the method of science. The technique that has been used to achieve and learn our current knowledge of the natural world is the same technique constructivists believe humans use to learn. Thomas Kuhn's (1970) description of science is one of the major influences of the contemporary constructivist theory. Piaget's mental functioning model, which provided the initial framework of constructivism, is synonymous with the scientific method. One of the advantages of the instructional methods that have arisen from constructivism, such as inquiry, is that these methods model the process of science. A student who is presented with an inquiry-based instructional environment is practicing science and thus developing an accurate understanding of science. If the process of science is an external indication of how people learn then constructivism is an accurate model of learning.

Constructivism influenced by Piaget's genetic epistemology and Vygotsky's social constructivism of reasoning is the theory base for this study.

What are Thinking Skills?

The discussion of improving students' thinking skills has been the focus of many research projects and books (e.g., Adey & Shayer, 1994; Barak, Ben-Chaim, & Zoller, 2007; Bruer, 1993; Burden & Williams, 1998; Chance, 1986; Feurstein, Rand, & Rynders, 1988; Greeno & Goldman, 1998; Halpern, 1992; Nickerson, Perkins, & Smith, 1985; Perkins, 1992; Perkins & Grotzer, 1997; Resnick, 1987;

Resnick & Klopfer, 1989; Schoenfeld, 1989; Sternberg, 1994; Sternberg & Spear-Swerling, 1996; Tishman, Perkins, & Jay, 1995; Zohar, 2004). Within these studies are a variety of definitions of thinking skills. Although the non-uniformity of the construct is not surprising, it does make establishing a precise definition troublesome. Resnick (1987) wrote that thinking skills resist precise forms of definition. She states that although some key features of higher order thinking cannot be defined exactly, higher order thinking skills can be recognized when they occur. Some of the characteristics of higher order thinking according to Resnick are: it is non-algorithmic, it tends to be complex, it often yields multiple solutions and it involves the application of multiple criteria, uncertainty, and self-regulation.

In his extensive review of formal reasoning research, Lawson (1985) determined that a number of formal tasks are reliable measures of a general mode of formal reasoning and that formal thought represents a general mode of intellectual functioning which in turn consists of identifiable reasoning patterns. The reasoning patterns Lawson referred to consist of the formal thinking skills Piaget and Inhelder identified in *GLT*. Those skills, which are defined in Table 2.1, include the control and exclusion of variables, classification, ratio and proportion, compensation and equilibrium, correlation, probability, formal models, logical reasoning, and hypothetico-deductive reasoning. Generally described, higher order thinking skills embody the ability to dissociate general ideas or concepts from the contexts in which they were learned and the ability to manipulate those concepts by integrating them into universal generalizations or by taking these generalizations back to their first principles. Higher order thinking is hypothetico-deductive; an individual with higher order thinking skills is able to conceive of new ideas, concepts, hypotheses or principles, explore their implications and then test for their validity.

Table 2.1 ***Summary of Formal Thinking Skills*** **(Cracolice, 2005, pp. 18-19)**

Formal Thinking Skill	Description
Control and exclusion of variables	Holding *n* independent variables and one dependent variable in mind, and considering the possible effects of each independent variable on the dependent variable.
Classification	The processes of understanding the possible ways that a classification may be carried out, understanding that any classification operation is part of a hierarchical system, selecting different criteria for different purposes, an understanding that one particular criterion does not necessarily allow prediction of others.
Ratio and proportion	Ratio: $y = mx$ (as x goes up, so must y); Proportionality: Comparison of two ratios.
Compensation and equilibrium	Compensation: $yx = m$ (as y goes up, x must come down); equilibrium: $ab = cd$.
Correlation	Determination of correlation among variables.
Probability	Simple sampling procedures; acceptance of the probabilistic nature of natural relationships.
Formal models	Model: representation of something else; working model: has different parts which move and which hold the same relationships to one another as in the real thing; formal model: a working model in which the moving parts are abstract entities which have to be imagined.
Logical reasoning	The ability to analyze the combinatorial relations present in information given.
Hypothetico-deductive reasoning	The ability to formulate and test alternative hypotheses against given data.

Measurement of Thinking Skills and Intelligence

In many fields there has been a close link between the development of theory and the development of good principles of measurement. However, in psychology this link has not been traditionally strong due to the divergence between quantitative and qualitative research methods. These research methods have been seen by some (e.g., de Vries, 1974) as mutually exclusive and by others (e.g., Andrich & Styles, 1994) as complementary. Michell (1999) traced the history of measurement in psychology, and addressed the issue of whether psychological attributes really are quantitative. He concluded that there are many aspects of human life that are non quantitative, but nevertheless can be investigated in a scientific manner in terms of their categories. Early measurement practices assumed a connection between intelligence and physical characteristics such as skull circumference and brain volume. Binet and Simon (1980) developed the first individual test of intellectual functioning in response to a need to identify children for special education. They developed a psychological scale with a continuum based on children's latent ability, with questions ordered according to difficulty and the age at which children could be expected to answer them. Although the tests of Binet and Simon assumed the development of intelligence with age, too often the results of such tests have been interpreted as the measurement of an innate unalterable ability.

Formal Thinking Skills

Early research work in formal reasoning used individual clinical interviews to assess intellectual development similar to the clinical method Piaget and Inhelder used (e.g., Lawson & Renner, 1974). Because of the time consuming nature of the interview, both for the researcher and the subjects, researchers have developed pencil and paper assessments that can be conveniently administered simultaneously to a large sample of people (Lawson, 1978; Shayer, Adey, & Wylam, 1981; Staver & Gabel, 1979; Tobin & Capie, 1981). This method also lends itself to statistical analysis and evaluation because the results are directly quantifiable. The most common format for the tests is paired multiple-choice questions that require subjects to respond to a question or make a prediction and then select an explanation for their initial response.

The test of cognitive developmental level used in this study is the Classroom Test of Scientific Reasoning (CTSR) (multiple-choice version, revised edition, August 2000). The test is a 24 item multiple choice test of developmental levels, specifically, formal-level reasoning (Lawson, 1978). The items in the test are drawn from the 16 binary operations and the INRC, described in chapter 17 of *GLT* (Inhelder & Piaget, 1958). The validity of the CTSR has been confirmed multiple times (e.g., Lawson 1978; 1992; Lawson, Baker, DiDonato, Verdi, & Johnson, 1993). Face validity was confirmed by polling a panel of six judges who are considered experts due to their professional involvement with Piagetian research; they responded with 100% agreement that the CTSR test items appeared to require concrete and/or formal reasoning (Lawson, 1978). Convergent validity was verified by testing to determine whether the CTSR test total scores and the level of subject response on a separate task that measures formal reasoning (Piaget's bending rods and balance beam task) were measuring the same psychological parameter (e.g., formal thought). There was a high correlation (0.76, $p < 0.001$) between the two tasks. Factorial validity was confirmed by submitting the CTSR and four Piagtian interview tasks (conservation of weight, displaced volume, bending rods, the balance beam) to a principal components analysis. The CTSR and the interview tasks loaded heavily on the same factor, which supports the hypothesis that they are measuring aspects of the same psychological parameter (e.g., formal-operational reasoning) (Lawson, 1978). The principal components analysis suggested that three, not two, identifiable psychological parameters are being measured. Factor 1 can be interpreted as "formal reasoning" and factor 3 as "concrete reasoning" as measured by the conservation of weight (the initial question on the CTSR). Factor 2 represents "early formal reasoning". This allows subject responses to be scored as early formal-operational as well as fully formal-operational. The CTSR was chosen for this study due to its validity, reliability, and availability to the researchers.

Because the CTSR items are drawn from the actual logical operational processes described by Inhelder and Piaget (1958) to model the development from concrete to formal operational thinking, it follows that the CTSR might be more free of retest effects that other types of tests (e.g., tests that measure what has been learned, rather than the capacity to learn).

Intelligence

There are three main scientific paradigms that have conceptualized the question of intelligence (Adey, Csapo, Demetriou, Hautamaki, & Shayer, 2007). There is the psychometric approach, which moves toward the conception of general intelligence, there is the developmental approach mapped out by Piaget and described in this literature review, and there is the information processing approach, which uses a computer-like analogy to describe the mind. Each of these models addresses some of the characteristics of intelligence but none of them is able to completely describe intelligence. In determining the effectiveness of this study, students' intelligence will be measured according to the developmental theory of Piaget (CTSR) and the psychometric approach (Raven Progressive Matrices), due to the lack of an available and complete evaluation tool (to the author's knowledge) for the information-processing model, the students' intelligence will not be measured according to that theory. Piaget's developmental theory has been adequately described earlier therefore a brief history of the psychometric approach to understanding intelligence is presented here.

Numerous authors have detailed the history of the structural approach to intellectual assessment (Anastasi, 1988; Carroll, 1993; Horn & Noll, 1997; Sattler, 1992). Differential psychology's approach to assessing intelligence reflects two main purposes; (1) to identify and enumerate through statistical means the total range of cognitive abilities thus far discovered by researchers, in essence, to provide a map or structure of human intellectual functioning, and (2) to describe individual differences in intellectual functioning; in other words, to provide a system for ranking or classifying individuals based on their performance on cognitive measures (Carrol, 1993; Horn & Noll, 1997; Sternberg, 1997). Within the psychometric tradition, the finding that tests of cognitive abilities are positively correlated has led to defining intelligence based on those correlations.

According to Horn and Noll (1997), psychometric, or structural, approaches are based on the logic of correlation, or concomitant variation, the idea that if different measures vary together, the possibility exists that a common function is being measured. The authors state that, while "this is not necessarily true– measures can vary together and not indicate common functions" (p. 54), at an empirical level, concomitant variation signals a commonality:

> if findings of concomitant variation are replicated in different samples of people, at different times, in different places, and, in general, under a variety of circumstances, it becomes increasingly plausible that a common function is (or possibly several common functions are) indicated by the different measurement operations (p. 54)

When measuring cognitive abilities, most measures of intellectual abilities are consistently and positively correlated. This lends evidence toward the claim that concomitant variation exists among different kinds of cognitive abilities, a finding of positive manifold according to Horn and Noll (1997). They state "the well-replicated findings of positive manifold" (p. 54) can be interpreted to indicate either a single common function or more than one common function underlying intelligence. The authors argue that the difference is important to the study of human intelligence because it:

> Distinguishes two major kinds of theories. One kind of theory interprets positive manifold as indication, at some level of analysis, a single common factor and a concept of general intelligence. The second kind of theory considers the same evidence as indication more than one common factor–more than one kind of intelligence. (p. 55)

The debate over these two perspectives has stimulated considerable controversy for over a century, with both positions represented in current theoretical models. Specifically, in terms of a single factor model, Carroll's (1993) three-stratum theory is widely referenced in the literature. In the theory, a general intelligence factor *g* is proposed, with other second-order, broad factors subsumed under it. In contrast, Cattell and Horn (Horn & Noll, 1997) describe a multiple factor approach: fluid and crystallized (Gf-Gc) theory of intelligence. These theorists argue that Carroll's statistical analyses can be interpreted quite differently, with the results indicating the presence of several intelligences rather than a singular intelligence. The development of both approaches is rooted in the early work of such researchers as Spearman (1927) and Thurstone (Thurstone & Thurstone, 1941).

In general, the psychometric or structural approach utilizes factor analysis to create an architectural structure of human cognitive capabilities. In addition, it focuses on describing and classifying individual differences in ability based on performance on various measures of intelligence. However, important limitations to this approach should be noted. As Sattler (1992) points out, much of the difficulty surrounding psychometric approaches is that "the outcomes of factor analysis vary depending on the nature of the data, the type of statistical procedure, and the proclivities of the investigator in choosing names to designate the factors" (p. 46). Essentially, it is apparent that even given the same data set, factor analytic approaches can yield different factors, different organizations, and thus different explanations regarding the structure of intelligence.

So how general is intelligence? An exact number has not and probably will not be identified, it is apparent the extreme positions, those who propose that intelligence is completely dependent upon the *g* factor (e.g., Jensen, 1998) and those that proclaim that distinct abilities independently frame academic performance in different domains of knowledge and learning (e.g., Gardner, 1993; Thurstone & Thurstone, 1941) are not supported in the literature (Adey, Csapo, Demetriou, Hautamaki, & Shayer, 2007). The operation of general constraints on intellectual performance is strongly supported by the fact that significant and often substantial correlations are obtained between tests of different types of cognitive abilities, such as spatial, numerical, and verbal. On the other hand, only a part, no more than 25%-30% of the variance in different domains of learning and knowledge can be accounted for by measures of general intelligence, such as IQ (Adey, Csapo, Demetriou, Hautamaki, & Shayer, 2007).

Why are Thinking Skills Important?

The statement from the Educational Policies Commission (EPC) quoted on page 15 helps to answer this question: the ability to think "runs through and strengthens all other educational purposes" (1961, p. 12). In trying to determine the central purpose of education the EPC referred to the guiding principles of the US: the commitment to a free society and respect for the individual. The commission stated that the ability to formally reason (use the rational powers) is necessary to truly achieve freedom (1961, p. 4). Even in a free society one cannot be free unless they have a free mind.

It is vital that when students leave school they have the ability to learn and achieve their goals outside of school. Lawson, in his review of research on formal reasoning (1985), concluded that a substantial portion of adolescents and adults do not acquire formal reasoning patterns and that deficiencies in formal reasoning are a probable cause of achievement deficiencies in the sciences, mathematics, history, social studies, English, and in everyday contexts such as comparative shopping in a supermarket and making decisions regarding social issues and interpersonal relationships. If students do not achieve the ability to reason formally in school, it makes it less likely that they will become formal thinkers; thus impairing their ability to achieve their career and life goals.

In a study conducted at The University of Montana (Cracolice, Deming, & Ehlert, 2008) a sample ($N = 94$) of students taking a first-term general chemistry course were presented with paired questions that covered the same content area but differed in that one of the problems could be solved using a memorized algorithm while the other required a conceptual understanding of the topic. The success rates on the two problem types were analyzed as a function of the cognitive ability of the students as measured by the Classroom Test of Scientific Reasoning. The results showed that students at the formal-operational level performed significantly better than students at the concrete-operational level on both types of problems. Very few of the students (0% – 21%) who could not reason at the formal level were able to solve the conceptual problems. The authors claim that the results demonstrate that variation in scientific reasoning skills is one cause of the gap between algorithmic and conceptual problem-solving ability.

Summary

The familiar Chinese proverb "give a man a fish and you feed him for a day. Teach a man to fish and you feed him for a lifetime" also applies to education. A student who can formally reason no longer requires someone to teach her the content of a subject. She has the tools to teach herself. Teaching students to become higher order thinkers should be the ultimate goal of all educators. The research literature cited speaks to the necessity of developing students' formal reasoning skills as well as the evidence supporting the existence of such skills.

Plasticity of Intelligence – Can Thinking Skills be Taught?

As described above, research indicates that scientific literacy requires students to be formal reasoners. With the release of the NSES, the U.S. has established a goal that all students should achieve scientific literacy (NRC, 1996, p. ix). The predominate view in the United States is that intelligence is genetically predetermined (Neisser et al., 1996). Is it possible to teach students to become better thinkers? New methods in brain research as well as science education studies on formal reasoning interventions indicate that it is possible. The international comparative studies discussed in the introduction indicate that it may be necessary.

In Finland less than 5% of the overall performance variation lay between schools and in Iceland and Norway it was less than 10%. Other countries in which performance was not very closely related to the schools in which students were enrolled included Sweden, Poland, Spain, Denmark and Ireland as well as the partner countries Latvia and Estonia. In these high performing countries parents can rely on high and consistent performance standards across schools in the entire education system (Finland showed also the highest overall performance in science). This is not the case in the U.S.; there is a large amount of variation in school performance.

Less than 10% of the variation in student performance was explained by student background in five of the seven countries with the highest mean science scores of above 530 (Finland, Canada and Japan, and the partner countries/economies Hong Kong-China and Estonia). These countries demonstrate that quality and equity can be jointly achieved (compared to an OECD average of 14.4%). In the United States, the key issue to address is a relatively high number of students with low proficiency in science and other competencies: 9% of students performed at Levels 5 and 6 (Level 6 is the highest level), roughly the OECD average for these levels, but 24% were at Level 1 or below in science.

Some other factors that influenced student performance in science in different countries were that schools that divided students by ability for all subjects tended to have lower student performance, on average. Students in schools that practiced ability grouping for all subjects within schools scored 4.5 points lower than students in schools that practiced no ability grouping or ability grouping only for some subjects, all other things being equal).

The average amount of time students invested in learning for science, mathematics and language in school and during self-study also affected student performance. Students in schools with one additional average hour per week scored 8.8 points higher, all other things being equal and students in schools with one additional average hour per week for self-study scored 3.1 points higher, all other things being equal.

A report released by the National Center for Educational Statistics (NCES on-line,

2009) focused on classroom practice as seen in videotapes of 8th grade mathematics classrooms in the U.S. and in six top-performing nations that participated in the TIMSS videotape studies: Hong Kong, Japan, the Netherlands, the Czech Republic, Australia and Switzerland. The U.S. was ranked the lowest of these countries in both the 1995, 1999, and 2003 TIMSS surveys. The videotape report offers many insights into how mathematics is taught in the different countries, but presents few conclusions. While the report showed some general features among the countries, there was considerable variation in the teaching of 8th grade mathematics. Distinctions included the introduction of new content, the coherence across mathematical problems and within their presentation, the topics covered and the procedural complexity of the problems, and classroom practices regarding individual student work and homework.

Research in Brain Physiology

The rapid development of instruments that provide accurate real time physiological brain data has given researchers opportunities to investigate established learning theories such as constructivism. Using brain imagining tools such as magnetoencaphalography (MEG) (Hari & Lounasmaa, 2000) which has a spatial resolution of millimeters and a time resolution of milliseconds, electroencephalography (EEG) (Hudspeth & Pribram, 1990; Thatcher, Giudice, & Walker, 1987), magnetic resonance imagining (MRI) (Giedd et al., 1999; Sowell, Thompson, Holmes, Jernigan, & Toga, 1999) and techniques like event related brain potentials (ERPs) (Stauder, Molenaar, & van der Molen, 1993), which represent changes in the electrophysiological activity in the brain in response to a physical or mental event or in association with movement, have been used in research studies to investigate the link between cognition and brain physiology. The studies have led researchers (Hansen & Monk, 2002) to suggest several positions: (a) there appears to be maturation and changes occurring in the brain up to a much later age than expected (as late as 15 years), (b) there is some evidence of periods of rapid growth, which may suggest brain maturation is a key factor in determining the timing and course of cognitive development and when pupils may then be ready for the next 'stage', (c) the adult/child processing of stimuli may be different and equally children who are pre-operational may be processing information differently than those at an operational level, (d) there is some evidence for at least a second wave of over-production of synaptic connections that can be influenced by experience and hence, reflexively, influence cognitive development itself (post-adolesence), (e) there are suggestions of gender differences and (f) increased myelination is being linked with improved cognitive processing.

While there are many important consequences that can be drawn from these conclusions there are two potentially far-reaching educational implications (Cracolice, 2005): (1) the data provides physiological evidence in support of Piaget's theory that the potential for formal thinking ability begins with the onset of puberty, at about age 11 for girls and age 12 for boys (Hudspeth & Pribram, 1990; Sowell et al., 1999; Stauder et al., 1993; Thatcher et al., 1987), (2) the data indicate that if an adolescent is challenged to use their formal thinking ability, those brain cells and their connections will survive (Giedd et al., 1999). While this indication of cognition plasticity is promising, the converse situation is also possible; an adolescent who is not provided an environment where formal thinking is required will have more difficulty developing formal thinking skills later in life. Giedd describes it as a 'use it or lose it' situation where it is critical that a learning environment is provided during the middle school and high school years that helps students develop formal thinking skills; so that these students won't 'lose it.'

Formal Reasoning Interventions

Many attempts to accelerate cognitive development have been reported in the literature. Most of the earlier studies were rather limited in scope, consisting of short-term projects, rarely extending beyond two months at the rate of one intervention per week. Siegler, Liebert and Liebert (1973) taught 10-year-old children to use the control of variables schema to solve Inhelder and Piaget's pendulum problem. As with many of the earlier studies, there was no attempt to test for the transfer of this skill to the context of other tasks. Lawson and Wollman (1976) succeeded in teaching 10- to 12-year-olds to control variables, and went further to demonstrate the specific transfer of that skill to novel tasks that also involved the control of variables. In 1982 Lawson and Snitgen showed that college freshmen made significant increases in formal reasoning ability after exposure to a special one-semester biology program, but no evidence of generalized transfer to new contexts was demonstrated. A few short-term intervention studies support the notion that generalized transfer can occur from a cognitive acceleration program. Kuhn and Angelev (1976) gave 8- to 11-year-olds a problem solving exercise, where the children were required to explain their strategies by thinking aloud. The experimental group performed better than a control group on both a pendulum and a chemical combinations post-test, although the intervention exercise was based on a control of variables task. Similarly, Rosenthal (1979) found that general transfer took place in 15-year-old girls after two one-hour training sessions that were designed to equip them with the cognitive strategies for solving control of variables problems. Adey and Shayer (1990) suggested that interventions which result in general transfer provide students with the essential mental tools to enable them to construct the formal schemata for themselves. They hypothesized that it is the process of students constructing their own meanings that leads to the cognitive restructuring required for transition to the next stage of development. Shayer (1999) distinguished between context-independent and context-delivered interventions. A context-independent intervention, such as Feuerstein's Instrumental Enrichment (Feuerstein, Rand, & Rynders, 1988), is delivered as a discrete course, quite separate from the school curriculum. On the other hand, a context-delivered intervention, such as Adey and Shayer’s (1994) Cognitive Acceleration through Science Education (CASE), is situated in the context of a particular school subject. Adey reported that whereas both types of intervention bring about gains on psychological tests, only the context-delivered programs were accompanied by long-term effects on student achievement. The success of CASE in promoting the acceleration of formal thinking in school children in the UK has been clearly demonstrated (Adey & Shayer, 1994).

Another context-delivered formal reasoning intervention study and curriculum reform effort is the Thinking in Science Classrooms (TSC) project (Zohar, 1996; Zohar, 2004; Zohar & Nemet, 2002; Zohar, Weinberger, & Tamir, 1994) conducted in Israel. The project developed a set of learning activities that were specifically designed to foster inquiry, higher order thinking, and scientific argumentation in multiple science topics. The learning activities matched topics from the junior high school science curriculum. In-service professional development courses took place all over the country. In TSC, lesson instruction revolves around tasks and problems that students are asked to solve. For example, students may be asked to argue about bioethical dilemmas in human genetics, to criticize an article about the diminishing ozone layer, or to engage in open inquiry about vitamins. The cognitive demands for solving these tasks consist of multiple thinking skills. After engaging these thinking skills on a procedural level (e.g., completing the tasks and solving the problems), students engage in a metacognitive activity regarding these skills. Through guided discussions and activity sheets, students reflect on the thinking skills they have been using, make generalizations and rules regarding these skills and verbalize how, when, and why each specific skill is being used. Teachers are also advised to engage in transfer activities, directing students to additional circumstances (both in other school subjects and in everyday life) where the same thinking pattern (or skill) may be employed. Thus, thinking skills are embedded in science contents and are also addressed as explicit educational goals. One of the assumptions the project is based on is that teaching of higher order thinking must be systematic. The methodology used in the TSC project is to repeat the same skill in different scientific contexts and to apply it to various types of problems. Accordingly, several different types of learning activities were developed: learning activities that follow lab experiments, Invitations to Inquiry (Schwab, 1963), critical assessment of newspaper clips, investigation of microworlds, fostering argumentation skills, and open-ended inquiry learning activities. Evaluation studies have shown that students who studied with the TSC learning activities gained significantly higher scores on reasoning tasks and on science knowledge tests than students from comparison groups who studied in the traditional way (Zohar, 1996, 1999; Zohar & Nemet, 2002; Zohar et al., 1994).

The success of these context based thinking skill focused interventions makes them ideal models for teaching thinking skills. The CASE materials will be used in this study to improve both students higher-order thinking skills as well as their intelligence. An in-depth review of the project is described next.

A History of CASE in the United Kingdom

The British Social Science Research Council originally funded the CASE project as a research project. The project began at Chelsea College, London, with a pilot study known as CASE I (1981-1983). This was followed by the main project that included an evaluation of the intervention, CASE II (1984-1987). Six years of applied research under the direction of Michael Shayer and Philip Adey, with support from Carolyn Yates, were needed to design, generate and refine the methodology. In CASE III (1989-1991) the focus was on a detailed description of the teaching skills involved in the intervention program. CASE is now being taught at hundreds of schools throughout the UK, by teachers who have received training in the CASE classroom methods from the professional development programs based at King's College, London.

The results of the CASE II research showed that the two-year intervention had a substantial effect on the cognitive development on students, as well as a long-term effect on their school achievement (Adey & Shayer, 1990, 1993, 1994; Shayer & Adey, 1992a, 1992b, 1993). Reported effect sizes were between 0.67 and 1.12 standard deviations per school on the cognitive post-tests. A 30-percentile difference was found between the pre/post-test changes for students in eight CASE schools and norms for 14,000 British school children aged 10-16 years (Shayer, Küchemann, & Wylam, 1976; Shayer & Wylam, 1978). A long-term effect was seen in science three years after the intervention, as well as a far transfer effect, away from the context of delivery, in mathematics and English. Effect sizes were between 0.3 and 1.0 standard deviations, which correspond with a half, and one GCSE grade (Adey & Shayer, 2002). The CASE II results were based on relatively small-scale data from around 130 students in each of the experimental and control groups (Adey & Shayer, 2002).

More convincing evidence of the effect of the CASE strategies on cognitive development and school achievement came from the data subsequently collected from over two thousand pupils from 11 schools whose teachers participated in the 1994-1996 CASE Professional Development programs. The students in the CASE schools scored consistently higher grades than their peers in the control schools. The average gain in the GCSE for the CASE schools was 1.05 grades (0.6 standard deviations) in science, 0.95 grades (0.5 standard deviations) in mathematics, and 0.90 grades (0.57 standard deviations) in English (Adey & Shayer, 2002). The improved student achievement in subjects other than science has been attributed to the CASE intervention having an effect on general intellectual growth, rather on domain-specific skills (Adey & Shayer, 1994, 2002).

Adey (1992) reported gender differences in the long-term effects of the cognitive acceleration program. The proportion of girls reaching formal operational thinking did not increase after the age of 14 years, whereas this effect was seen later, at 15 years, in boys. Further, the age at which the program was started was found to be relevant. Boys who began CASE at age 12+ years performed significantly better than controls in science and mathematics in the GCSE, whereas 12+ girls performed better than controls in English. The boys who began at age 11 years, unlike their female peers, showed no effects of the intervention in the GCSE. Adey (1992) further showed that boys exposed to the intervention course achieved an average of 40% more grades of C or above in the science GCSE than did controls, whereas the gain for girls was lower, at 25%. This work raises the idea that there might be different critical periods of learning for boys and girls and that gender might also be related to performance in certain subjects.

High achievement gains were reported for the full ability range of pre-intervention students (Adey & Shayer, 1994). They concluded that the students who made the greatest gains in academic achievement were not restricted to those who had more ground to make up, nor to those who were more able and therefore perhaps more ready to move on to formal thinking.

Leo and Galloway (1996) argued that some of the results of CASE should be attributed to student motivation. They referred to research suggesting that children who have low self-concepts tend to lack metacognitive skills (Carr, Borkowski, & Maxwell, 1991) and offered this as an explanation for why some students might not respond to the CASE strategies.

Due to the success of CASE in the UK there have been several CASE studies implemented in other countries seeking to improve the science education achievement of their students. These studies are described below.

CASE in Pakistan

Iqbal and Shayer (2000) reported that the level of cognitive demand of the Pakistan science curriculum for 11 to 13 year olds was far in excess of the level of thinking of those students as revealed by Piagetian tests. This research lead to the introduction of the CASE intervention in three schools with the goal of improving the match between curriculum demand and students' ability.

Two fee-paying schools and one government school took part in the project and teachers attended professional development workshops in the CASE methods at the University of Punjab. Following the practice used in the United Kingdom, the intervention took place over a two-year period. A separate class of students who did not receive the intervention acted as a control group in each school. Pre- and posttests of cognitive development were conducted using *Science Reasoning Tasks* (NFER, 1979). Two posttests were carried out, one six months after the start of the intervention and the second a year after the intervention ended. The end of year examinations developed and administered by each school were used as the measures of student achievement. As these examinations were specific to each school, comparisons were made between experimental and control classes within schools, rather than between schools. Iqbal and Shayer (2000) reported that the proportion of students who showed evidence of formal operational thinking was higher in the students who had experienced the CASE intervention. The mean cognitive development level for the CASE students was found to be at the early formal stage (IIIA), whereas the mean for the control groups was at the early concrete level (IIA), even though the control groups in each school were initially superior to the experimental groups. Iqbal and Shayer (2000) found that the effect of the intervention was to change the mean of the experimental group on the pretest by about 30 percentile points in relation to British norms, an almost exact replication of the results in Britain (Adey & Shayer, 1993). They also reported significant gains with effect sizes between 0.47 and 1.18 standard deviations on the delayed post-tests.

Iqbal and Shayer suggested that girls might have gained benefit from the student discussion in CASE lessons, student discussion not being a common feature of science classes in Pakistan. Bridging, in which teachers helped students to connect the CASE ideas with other contexts, was thought to have been crucial to the success of the program.

CASE in Malawi

The effect of CASE on the performance of secondary school students has been investigated in Malawi (Mbano, 2003). The aim of the study was to discover whether evidence could be found for the critical period for cognitive transition from concrete to formal operations at 12 to 14 years of age. The sample population of 694 students included control and experimental groups of boys and girls from seven schools. The pupils in the experimental schools were taught CASE lessons at the rate of one lesson every two weeks. The teachers attended eight training workshops over a period of three years and were visited in schools at least twice a term. Two Science Reasoning Tasks (SRT) developed by Shayer et al. (1976) were the pre- and posttests used to assess cognitive development; SRT II (Volume and Heaviness) and SRT III (The pendulum). The SRT II (volume and heaviness) task is used to assess students who have attained early concrete operational thinking (IIA) to early formal operational thinking (IIIA). It tests whether students have attained the conservation of mass and volume and whether they can handle the compound variable of density. The SRT III (the pendulum) task is able to assesses students' cognitive development level from mature concrete (IIB) to formal operational generalization (IIIB). It tests if students have developed the concept of control of variables and exclusion of irrelevant variable strategies in designing experiments and analyzing data.

The Malawi School Certificate of Education results in biology, physical science, mathematics and English of the sample population were analyzed in order to explore whether the CASE intervention improved the academic performance of students. The older students, aged 16-17 years, in Malawi made similar cognitive gains to those reported for younger students in the British CASE studies. The effect size for girls was 0.9 standard deviation and for boys 1.3 standard deviations. The author interpreted these results as evidence that the critical period for cognitive transition from concrete to formal operations at 12 to 14 years of age does not exist. She also reported that girls, who were on average a year younger than boys in the same class, and older boys, had lower academic achievement than younger boys. The results of interviews revealed that CASE was seen to be beneficial by both teachers and pupils.

Summary

Both brain physiology research and the results of studies that have made teaching thinking skills an explicit goal indicate that thinking skills can be taught. Shayer and Adey's CASE project as well as Zohar's TSC program suggest that thinking skills should be taught in the classroom. It appears that there may be an optimal window for students to develop thinking skills during adolescence but more research needs to be done in this area. As the Malawi study demonstrated, older students can learn formal reasoning skills. One hypothesis is that there is an optimal window of opportunity for higher order thinking skill development during adolescence similar to the optimal language development period that has been found in children. Post-adolescent students may have more difficulty developing formal reasoning skills but it is still possible.

How Can Thinking Skills Be Taught?

The CASE project answers the question about whether thinking skills can be taught, but how are they taught? The CASE methods and materials are an inquiry-based constructivist instructional approach. This method has been shown to be more effective at developing students' thinking skills when compared to the traditional or expository approach.

Inquiry Instruction

Historical Background

Science, since becoming established in school curriculum at the beginning of the twentieth century, has been viewed by many educators as a body of knowledge that students must learn through direct instruction. This viewpoint has weathered inquiry-based calls for change and curriculum reform led by reformers such as John Dewey, Joseph Schwab, and F. James Rutherford throughout the history of science education. Although many scholars were involved in the development of the idea of inquiry, John Dewey first articulated the current concept of inquiry. He also contributed in bringing science as inquiry into the classroom (Crawford, 2000). Dewey argued that science teaching should emphasize science as a way of thinking rather than an accumulation of information (Bybee, 2000). He believed that children learn through extensive experience-based activities and discussions with one another. Dewey (1910, p. 125) stated:

> Such knowledge never can be learned by itself: it is not information, but a mode of intelligent practice, a habitual disposition of mind. Only by taking a hand in the making of knowledge, by transferring guess and opinion into belief authorized by inquiry, does one ever get a knowledge of the method of knowing.

Dewey proclaimed that science is more than a body of knowledge to be learned; there is a process or method to learn as well (Bybee, 2000).

Joseph Schwab provided a fundamental theme in the science curriculum reform in the 1950s and the 1960s (Wallace & Kang, 2004). Schwab proposed that the public needed new ideas and doctrines of science as the world changed, and these fresh scientific conceptions could be acquired only by the inquiry approach (Schwab, 1962). He articulated the concept of teaching science as inquiry, in which this process is not only a presentation of facts, but also an interpretation of facts through experimentation. Schwab urged science teachers to use laboratory experiences that included active questioning and investigation (Bybee, 2000).

In 1964, James Rutherford, well known as a "science reformer," further developed the concept of inquiry in modern education. Rutherford (1964) made a distinction between inquiry as content and as a technique. The former referred to studying about the nature of scientific inquiry. The latter referred to using inquiry methods as an instructional strategy. Later, Rutherford claimed inquiry should deliver both content and process to learners in *Science for All Americans* published in Project 2061 (AAAS, 1990). In this book, he urged science teachers to gain sufficient knowledge about inquiry to practice it in their classrooms. Rutherford made a great contribution by emphasizing a significant aspect of the nature of science as well as inquiry pedagogy in teaching science.

In the 1970s and 1980s, the National Science Foundation supported a project that synthesized the status of education in the United States (Bybee, 2000). This analysis, called Project Synthesis, revealed that the definition of inquiry was not clear, even though the science community was using the term constantly in science teaching. The term "inquiry" was used in a variety of ways, including both inquiry as content and inquiry as process skills. In addition, the analysis showed that most teachers viewed inquiry as only process skills and that teachers used inquiry infrequently in their teaching practice (Hurd, Bybee, Kahle, & Yager, 1980). The evidence from this project also indicated that "although teachers made positive statements about the value of inquiry, they often felt more responsible for teaching facts, 'things which show up on tests,' 'basics' and 'structure and the work ethic'" (Welch, Klopfer, Aikenhead, & Robinson, 1981, p. 48). Costenson and Lawson (1986) suggested that teachers must clearly understand the definition of scientific inquiry and also acquire the skills necessary to implement inquiry in science classrooms successfully.

Following Project Synthesis, the American Association for the Advancement of Science initiated Project 2061, which focused on a long-term science education reform (Shymansky & Kyle, 1988). Project 2061 published *Science for All Americans* emphasizing scientific literacy for all students in 1989, and also produced *Benchmarks for Scientific Literacy* as a guiding tool for science curriculum design in 1993 (Collins, 1998). Project 2061 stated specific goals and standards for teaching science as inquiry in the classrooms.

During this period, the National Science Teachers Association, along with other professional organizations, including the American Chemical Society and Biological Science Curriculum Study, initiated a project called Scope, Sequence, and Coordination, which highlighted the reconstruction of science education for secondary schools (NRC, 1996). Scope, Sequence, and Coordination promoted the development of an innovative science curriculum that emphasized "hands-on science." Through these projects, the science education community developed and provided "authentic inquiry-based science activities" for K-12 students (Windschitl, 2002).

In 1996, the National Research Council published the *National Science Education Standards* (NSES), which presented the role of inquiry-based science instruction (Keys & Bryan, 2001). The NRC (1996) declared that "inquiry into authentic questions generated from student experience is the central strategy for teaching science" (p. 31) and that the student should "engage in selected aspects of inquiry as they learn the scientific way of knowing the natural world…and also should develop the capacity to conduct complete inquiries" (p. 23). In these passages, the NSES explicitly stated that students in K-12 classrooms developed both abilities and understanding of scientific inquiry. The NSES prompted the science education community and the public to focus again on inquiry. Most importantly, it provided the goal of teaching science as inquiry.

Definition of Inquiry-based Science Instruction

Inquiry has been a perennial and central term in science education reforms in the United States (Abd-El-Khalick, Boujaoude, Lederman, Mamilok-Naaman, Hofstein, Niaz, Treagust, & Tuan, 2004). The term "teaching science as inquiry" has been frequently used in many different ways including doing science, hands-on science, discovery learning, project-based learning and real-world science (Crawford, 2000). As it was used in many terms, inquiry was ambiguously defined sometimes as a way to teach science, or a method to address important educational goals.

However Crawford (2000) pointed out that the term "inquiry" should not be equated with the terms "hands-on science" or "discovery learning" in which a series of hands-on activities are provided, often without science content. Discovery learning, often used as synonym to hands-on science, refers to the learning environment in which students are free to work with little or no guidance, and it often results in clueless learning (Mayer, 2004). The American Association for the Advancement of Science also stressed the weakness of hands-on activities as inquiry. "Hands-on experience is important, but it does not guarantee meaningfulness." (p. 319)

The concept of inquiry-based science teaching was well grounded by Joseph Schwab during the 1960s (Schwab, 1962). He envisioned the concept of inquiry as the learning process that includes a presentation of facts and also understanding of the facts through experimentation. Moore (1993) described science as both knowledge of the natural world and as processes used to acquire that knowledge. Like Moore, Wheeler (2000) and Bybee (2000) believed that teaching science as inquiry should engage students with content to be learned through inquiry activities. The inquiry activities involved observing, asking questions, and making predications and interpretations.

Over the past years, many researchers have examined the definition of inquiry. However, it was the *National Science Education Standards* that presented the concept of inquiry-based science instruction, which reflects upon the current consensus among the science education community. The NSES refers to inquiry as an instructional approach that helps K-12 students develop understanding of scientific knowledge as well as skills to conduct inquiry. These skills (Table 2-2) include identifying and posing scientific questions, designing and conducting investigations to answer the question, analyzing data to construct explanations, and communicating the findings (NRC, 1996; 2000). Inquiry has become a particular way of teaching and learning science. Inquiry-based instruction has provided many roots that have given rise to developing science content and scientific inquiry among students. The NSES also emphasized that students should develop both abilities and understanding of conducting inquiry in the classroom.

Table 2.2 Essential Inquiry Features and Its Variations in the Classroom (NRC, 2000, p. 85)

Essential Features		Variations			
1	Learner engages in scientifically oriented questions	Learner poses a question	Learner selects among questions, poses new questions	Learner sharpens or clarifies question provided by teacher, materials, or other source	Learner engages in question provided by teacher, materials, or other source
2	Learner gives priority to evidence in responding to questions	Learner determines what constitutes evidence and collects it	Learner directed to collect certain data	Learner given data and asked to analyze	Learner given data and told how to analyze
3	Learner formulate explanations from evidence	Learner formulates explanation after summarizing evidence	Learner guided in process of formulating explanations from evidence	Learner given possible ways to use evidence to formulate explanation	Learner provided with evidence and how to use evidence to formulate explanation
4	Learner connects explanations to scientific knowledge	Learner independently examines other resources and forms the links to explanations	Learner directed toward areas and sources of scientific knowledge	Learner given possible connections	
5	Learner communicates and justifies explanations	Learner forms reasonable and logical argument to communicate explanations	Learner coached in development of communication	Learner provided broad guidelines to use sharper communication	Learner given steps and procedures for communication
More-------------Amount of Learner Self-Direction--------------Less **Less----------Amount of Direction from Teacher or Material----------More**					

The Learning Cycle

The learning cycle is an inquiry-oriented pedagogy that can be used as a framework for entire programs, specific units, and individual lessons. The instructional model is effective in the curriculum development process as well as in the enactment of curricular materials in the classroom. The learning cycle was first proposed in the early 1960s by Atkin and Karplus (1962) and was used in the Science Curriculum Improvement Study (SCIS). One of the most common learning cycle models uses a five-phase model: engage, explore, explain, elaborate, and evaluate (the 5E model). In the engage phase the instructor or a curriculum task accesses the learners' prior knowledge and helps them become engaged in a new concept through the use of short activities that promote curiosity and elicit prior knowledge. During the exploration phase students are provided with experiences with a common base of activities within which current concepts, processes, and skills are identified and conceptual change is facilitated. Learners may complete lab activities that help them use prior knowledge to generate new ideas, explore questions and possibilities, and design and conduct a preliminary investigation. The explanation phase focuses students' attention on a particular aspect of their engagement and exploration experiences and provides opportunities to demonstrate their conceptual understanding, process skills, or behaviors. This phase also provides opportunities for teachers to directly introduce a concept process or skill. Learners explain their understanding of the concept. An explanation from the teacher or the curriculum may guide them toward a deeper understanding, which is a critical part of this phase. In the elaboration phase, teachers challenge and extend students' conceptual understanding and skills. The students develop deeper and broader understanding, more information and adequate skills through new experiences. They apply their understanding of the concept by conducting additional activities. The last phase, the evaluation phase, provides opportunities for teachers to evaluate student progress as well as encourage students to assess their understanding and abilities.

The learning cycle was developed from research on student learning, particularly Piaget's mental functioning model. The theory describes how a student learns, regardless of their developmental level. According to the model, there are four steps of mental functioning: assimilation, disequilibrium, accommodation, and organization. The learning cycle is derived from these four steps. The exploration phase of the learning cycle is directly related to the first step, assimilation. A person assimilates by taking in information and filtering it through his or her mental structures. Assimilation is the mental activity of taking ideas from experience. If the information taken in fits into existing mental structures, a person is in equilibrium; if the information does not fit, the individual is disequilibrated. The learning cycle attempts to cause disequilibration during the explanation phase by forcing students to examine and explain the trends in the data that they collected in the exploration phase. Once an individual is disequilibrated, Piaget's theory states that people will engage in adaptational behavior so as to reequilibrate themselves. This desired reequilibration occurs when a person accommodates. In addition to causing disequilibration, the explain phase of the learning cycle is also when students are expected to accommodate to new ideas. Students are expected to redefine, change, or invent mental structures during this phase. When students accommodate, they "invent" a new concept. The last step in mental functioning is organization, when a person relates their new or changed mental structures to other ones. A person puts the "accord of thought with itself" (Piaget, 1963, p. 8). The elaborate phase of the learning cycle is derived from this step. When students are exposed to a concept in different situations, students are led to organize their mental structures that relate to that concept.

Table 2.3 Piaget Functioning Model and the Learning Cycle Approach
(Abraham, 2005, p. 45)

Piaget's Mental Functioning Model	The Learning Cycle	Learning Activities and Materials
Assimilation	Exploration	Data collection and analysis
Disequilibrium and Accommodation	Explanation	Conclusions and/or interpretation
Organization	Elaboration	Application activities

Lawson (1995) completed a comprehensive review of more than 50 research studies on the learning cycle that were conducted through the 1980s. Many of the studies focus on the efficacy of the learning cycle for addressing student misconceptions in science. Ten of the studies cited by Lawson investigated the impact of the learning cycle approach on subject matter knowledge of elementary through undergraduate students. Six of the studies (Bishop, 1980; Bowyer, 1976; Nussbaum, 1979; Renner & Paske, 1977; Saunders & Shepardson, 1987; Schneider & Renner, 1980) found that students who were taught using the learning cycle had greater gains in subject matter knowledge than students taught using direct or expository instruction. Two of the studies (Bishop, 1980; Schneider & Renner, 1980) found that the achievement gains among students who experienced learning cycle instruction persisted in delayed post-tests of students' understanding of science concepts. The other four studies found no differences in achievement between students who experienced learning cycles and those who received traditional instructional formats (Campbell, 1977; Davis, 1978; Horn, 1979; Vermont, 1984).

A review by Guzzetti, Snyder, Glass, & Gamas (1993) used cluster analysis to identify instructional approaches that had the largest effects on conceptual change. They found that the average effect of the learning cycle on conceptual change was about one-quarter of a standard deviation unit, with larger effects when additional strategies (such as prediction laboratories) were included as part of the learning cycle. They further noted that when a learning cycle that included laboratory work was compared with one that did not include a laboratory, the differential effect was about one and one-half standard deviations. When a laboratory was combined with other forms of traditional instruction (i.e., lecture, demonstration, and nonrefutational text not in a learning cycle format), however, it was much less effective. Comparison of a prediction laboratory–learning cycle combination with traditional instruction showed positive results in favor of the former, by one-third of a standard deviation.

Many of the studies reviewed by Lawson investigated the impact of learning cycle instruction on students' formal reasoning abilities. This instructional model consistently showed superior results over more traditional instructional approaches for cultivating the development of these abilities; 17 of 18 studies had positive results (e.g., Carlson, 1975; McKinnon & Renner, 1971; Renner & Lawson, 1975; Saunders & Shepardson, 1987; Schneider & Renner, 1980; Wollman & Lawson, 1978).

Studies reviewed by Lawson assessing concrete reasoning skills all showed that instruction based on the learning cycle was more effective than traditional instruction. Renner, Stafford, Coffia, Kellogg, and Weber (1973) concluded that first graders who used the SCIS materials had greater gains in reasoning skills, as measured by Piagetian conservation tasks, than first graders who used a textbook. Linn & Thier (1975) found that fifth graders who were taught using the SCIS materials performed better than those who did not on tasks that required identification and compensation of variables.

Research by Renner and his colleagues (Renner, Abraham, & Birnie 1985; Renner, Abraham, & Birnie, 1988) investigated the efficacy of the learning cycle sequence. They determined that the learning cycle is most effective when used as originally designed.

Summary

Inquiry instruction has been shown to be not only the most effective method of teaching thinking skills but it is also superior to traditional instructional methods at teaching science content. However, since the release of the NSES, which argues the necessity of teaching by inquiry, student performance in science in the U.S. has decreased. Does this mean that the research showing the superiority of inquiry is incorrect? That question is still in doubt, in part due to the lack of comprehensive research done on inquiry instruction. The primary problem is the difficulty of teaching by inquiry. A successful inquiry-based classroom requires the instructor to understand inquiry, and as stated above many instructors do not. Many of the processes of inquiry also require higher-order thinking and it is likely that some instructors are not fully formal thinkers, which is a probable cause of many instructors not understanding inquiry. Students' lack of formal reasoning ability also contributes to the problem. An emphasis in thinking skills within the science curriculum has the potential to drastically improve the state of science education in the U.S. Tomorrow's teachers, if taught to formally reason, are going to be more successful in teaching their students thinking skills.

Conclusion

This literature review first described the theory of learning that the study is predicated on. According to the constructivist theory of learning, students learn by constructing their own understanding of the universe based upon the data that they filter through their senses and previous experiences. Information from a person or a source is not transferred perfectly intact to the learner. This has immense implications for how students should be taught and this study will help to lend evidence supporting or undermine this theory.

After addressing the learning theory that the research study is founded on, four questions were asked that sought to answer how the central purpose of education (developing students thinking skills) could be accomplished: (1) What are thinking skills? (2) Why are thinking skills important? (3) Can thinking skills be taught? and (4) How can thinking skills be taught?

Thinking skills were identified as Piaget's formal reasoning tasks. Specifically (a) the ability to control and exclude variables in an experiment, (b) the understanding of the processes of classification, (c) the context-independent understanding of proportionalities and equilibrium, (d) the ability to determine the correlation among variables, (e) the acceptance of the probabilistic nature of natural relationships, (f) the understanding of formal models, (g) the ability to analyze the combinatorial relations present in given information, and (h) the ability to formulate and test alternative hypotheses against given data. The validity and importance of these skills was described under the review of Piaget's genetic epistemology theory, which includes the research done on formal operational thinking (p. 17).

The importance of thinking skills was answered by reporting the necessity of higher-order thinking in understanding science and in truly being an independently thinking human being.

In answering the question of whether thinking skills can be taught the latest brain physiology research was reviewed as well as multiple studies that have been successful in teaching thinking skills, using the CASE project in the UK as the primary example.

Finally the review of inquiry instruction indicating the effectiveness of the pedagogical technique in teaching students thinking skills and science content answered the question of how thinking skills can be taught.

CHAPTER III

RESEARCH METHODOLOGY

This chapter describes the research design used to investigate the research problem, the procedure used to choose the subjects of the study, the experimental treatment procedure and design, and the control group characteristics. The chapter also covers the measures that will be used to investigate the treatments effectiveness as well as the statistical analysis used in the study.

Research Design

The research was conducted using an information-oriented case study model that followed a quantitative pretest-posttest control-group design for formal reasoning abilities and intelligence (Campbell & Stanley, 1963). The design controls for the eight primary threats to internal validity: (1) the history effect, (2) maturation, (3) the testing effect, (4) instrumentation effect, (5) statistical regression, (6) differential selection, (7) experimental mortality, and (8) selection–maturation interaction. The small scale of the study helped to minimize or eliminate the remaining four threats to internal validity identified by Cook and Campbell (1979): (1) experimental treatment diffusion: only one treatment student left the study due to a previously scheduled family vacation. (2) Compensatory rivalry by the control group and (3) resentful demoralization of the control group: typically only two to four treatment students were removed from each class and the control students were usually not aware that the treatment was occurring; the study only occurred over a brief time (five weeks); the researcher did not observe any signs that the control group experienced any of the above threats. (4) Compensatory equalization of treatments: all of the treatment students experienced the same treatment and the control group was strictly defined and not involved in the treatment.

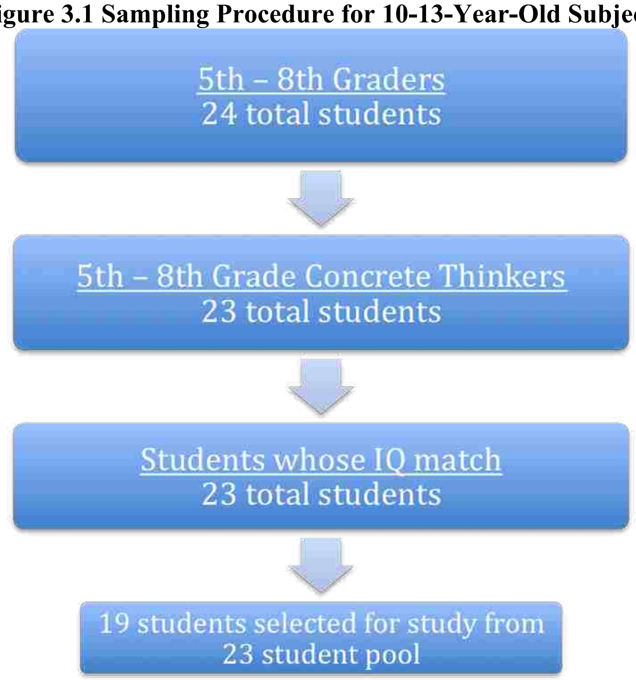
Due to the large demand of students' time and the exploratory nature of the case study, the sample size in the study will be small. This may weaken the external validity of the study, including the population validity and ecological validity. The limited external validity should not inhibit the effectiveness of the study in that it will show the potential of improving students' intelligence and the plasticity of intelligence at different ages.

Sampling Procedure

An information-oriented case study design was employed in selecting the subjects to insure subject equivalence. The final group of subjects consisted of a minimum of two students, one control subject and one treatment subject, for each age group and both genders, beginning from age ten (fifth grade) to sixteen (junior year in high school). There were a total of 32 subjects.

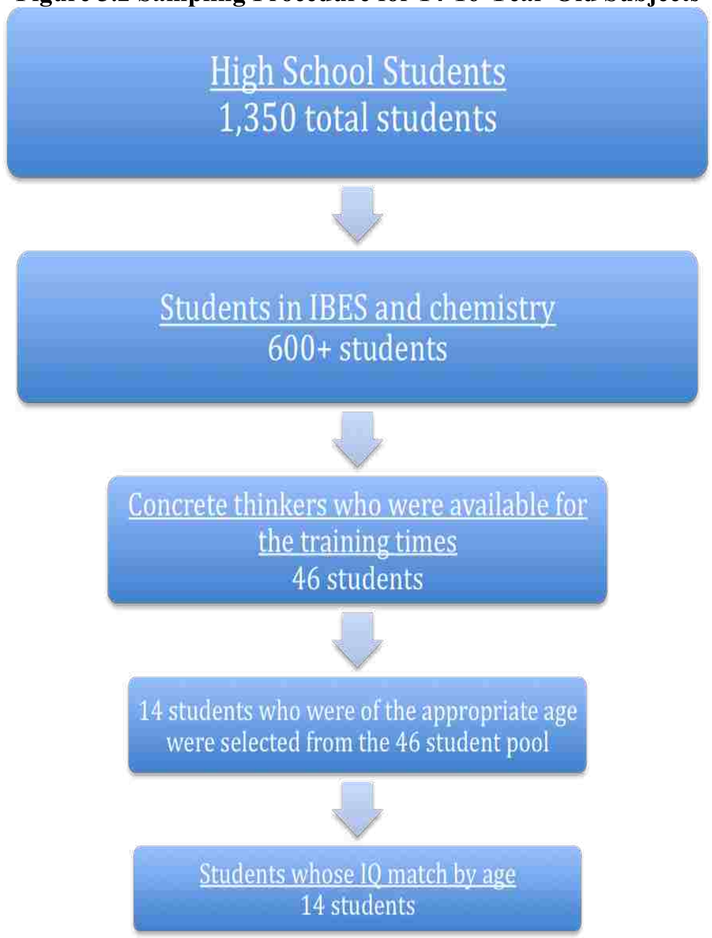
The students were selected based upon their age, gender, scientific reasoning ability, and intelligence. The subjects aged ten to thirteen were drawn from a rural multi-grade school in Lolo, Montana with 56 students in kindergarten through eighth grade. The fifth and sixth grades (ages 10-11) are combined in one classroom, as are the seventh and eighth grades (ages 12-13). All of the fifth through eighth grade subjects, except one eighth grade male, were concrete thinkers according to the Classroom Test of Scientific Reasoning (multiple-choice version, revised edition, August 2000). For the study the following subjects were selected from the rural school: two 10-year-old females, three 10-year-old males (1 treatment, 2 control), three 11-year-old females (2 treatment, 1 control), two 11-year-old males, two 12-year-old females, two 12-year-old males, three 13-year-old females (2 treatment, 1 control), and two 13-year old males. Every subject's intelligence was scored as mentally average (Table 3.1) for his or her age according to the Raven Progressive Matrices intelligence measure (Raven, Raven, & Court, 1998). The subjects were randomly assigned to the treatment and control groups.

Figure 3.1 Sampling Procedure for 10-13-Year-Old Subjects



The students aged fourteen through seventeen came from a high school in Missoula, Montana with approximately 1,350 students. All of the high school students (excepting special cases) are required to take an integrated biology and earth science course (IBES) their freshman (IBES I) and sophomore year (IBES II). The 14-year-old and 15-year-old students were selected from these two courses. The 16-year-old students were selected from the junior year chemistry course at the high school. All of the IBES I and IBES II as well as the chemistry students were tested on their formal thinking skills before the study. From the pool of students in those courses, the subjects who were identified as (a) concrete thinkers, (b) had a mentally average intelligence for their age (Table 3.1), and (c) were available for the training times were selected. The selected students were randomly assigned to the control and treatment groups. The following subjects were selected from the high school: two 14-year-old females, two 14-year-old males, two 15-year-old females, two 15-year-old males, three 16-year-old females (2 treatment, 1 control), and two 16-year old males.

Figure 3.2 Sampling Procedure for 14-16-Year-Old Subjects



Experimental Treatment and Procedure

The procedure consisted of two pre-tests of two different constructs administered at the same time followed by a four-week period of training for half of the students selected from the original sample. Two separate post-tests, identical to the pre-tests, were administered to all of the subjects after the training. Five weeks passed between the pre-tests and post-tests. The two tests measured students' level of formal thinking ability and intelligence. The subjects' formal thinking ability was assessed with the Classroom Test of Scientific Reasoning (described below). The students who were classified as formal operational, transitional, and early-transitional thinkers were excluded from further participation in the study, leaving only the concrete thinkers. The students were then selected for the study so that there was a minimum of two subjects for each age group and both genders. The selected students, already matched for scientific reasoning ability, then had their intelligence measured using the Raven Progressive Matrices test (described below) to insure that their IQ was equivalent by age. A minimum of one student from each age group was then randomly allocated to a training group. The training consisted of twice-per-week 45-minute training interventions for four weeks. Each student in the treatment group was matched according to age, gender, formal reasoning ability, and intelligence with a control student.

Treatment Training Procedure

The author of the research study conducted the training. The intervention began in November 2009. The students were paired in the training sessions accordingly: (a) 10 and 11 year-olds (born 11/5/97 to 11/4/98 and 11/5/96 to 11/4/97), (b) 12 and 13 year-olds (born 11/5/95 to 11/4/96 and 11/5/94 to 11/4/95), (c) 14 and 15 year-olds (born 11/5/93 to 11/4/94 and 11/5/92 to 11/4/93), (d) 15 and 16 year-olds (born 11/5/92 to 11/4/93 and 11/5/91 to 11/4/92). The four training groups had a minimum of six students and a maximum of ten students. The training sessions consisted of inquiry-based instruction designed to develop the students' formal thinking abilities, specifically the ability to control and exclude variables in a study and the ability to manipulate ratios and proportionalities. The training was limited to two formal thinking skills because of the four-week time frame that was available for the researcher to conduct the treatment. Each formal thinking skill was focused upon for two weeks. The training groups provided students with an atmosphere of collaborative learning. The content of the intervention sessions consisted of the *Thinking Science* (Shayer, Adey, & Yates, 2001) activities that were used in the CASE program described in the literature review. The *Thinking Science* kit (available commercially which prohibits its placement in the appendix) has thirty lessons that focus specifically on one formal thinking skill per lesson. The kit provides instruction on the following formal thinking skills: (1) the identification and control of variables, (2) proportional reasoning, (3) correlational reasoning, (4) probabilistic reasoning, and (5) hypothetico-deductive reasoning. Lessons 1, 2, 4, and 5 were used to assist students in developing the ability to identify and control variables. Lessons 8, 9, 10, and 30 were used to assist students in develop proportional reasoning.

A typical CASE lesson takes approximately one hour to administer. Lesson plans from the *Thinking Science* kit include four phases: concrete preparation, work on the task, construction/metacognition, and bridging. In the first phase the researcher introduces the students to a problem, such as finding out why some objects float while others sink (Lesson 27). Lesson 27 tackles the compound variable *density* through hands-on experiences with buoyancy. In trying to predict whether or not jars will float or sink, students discover that neither volume nor mass alone provide sufficient information for an accurate prediction to be made. Rather, both mass and density must be considered when predicting whether a jar will float or sink. The researcher prepares the students to engage with the problem by setting it in context and introducing the new vocabulary the students will need to talk about the problem. The strategy used is one of concrete experience—in this case jars of the same volume but different masses are tested in a tank of water. The conclusion is that the heavier the jar, the more likely it is to sink. The researcher then has the students repeat the experiment with jars of equal mass but different volumes. The conclusion here is a little more confusing, that the smaller the jar, the more likely it is to sink. The data is recorded in a classification table.

The researcher now introduces the element of cognitive conflict by providing two new jars, which do not perform according to the children's predictions. For example, jar X is the same volume as jar 3 (that floated), and the same mass as jar C (that floated), but in fact sinks. The sinking of jar X is a discrepant event for many students, providing them with cognitive dissention. The aim of this cognitive conflict phase of the lesson is to engage students in a struggle with the problem, and to challenge their prior knowledge and personal theories. The researcher plays a vital supportive role by challenging the students to look at the problem from different perspectives and by promoting a discussion of the difficulties experienced. It would typically take about 15 minutes to administer this introduction to the lesson. Following the introduction, students typically collaborate together in small groups of four or more to work on a task. In the lesson, students play a card game that provides a further opportunity for them to discover that both volume and mass have to be considered before an accurate prediction can be made about whether something will float or sink. Twenty to thirty minutes are usually allowed for the group to perform the task and discuss their solutions with each other and with the researcher. Typically, each group would then present their results to the whole class with the researcher chairing the discussion. Cross-questioning of students by each other is encouraged. The researcher uses questions such as “How did you solve that?” and “Can you explain why you think that?” Students are prompted to reflect collaboratively on ideas that emerge in the whole class discussion. Worksheets guide the students in constructing their own knowledge and in revising their former theories. Metacognition occurs when students not only become conscious of their own thinking, but develop and practice their explicit thinking processes.

The final stage of bridging takes place when the researcher helps the students to link the new thought processes to other areas of the science curriculum in particular, as well as to their everyday experiences in general. This is often achieved by the researcher inviting students to think of other contexts where the ideas might be useful. In Lesson 27, the problem sheet consolidates the ideas of floating, sinking, and compound variables. It also introduces a new compound variable momentum. The two variables in this case are mass and speed, and the compound variable is the product of these two simple variables, rather than the ratio as is the case with density.

Control Group

The training sessions for all the subjects in the treatment group occurred during the students' regularly scheduled science course. The training sessions replaced the class time that they missed. Therefore, the control students attended the science course while the students in the treatment groups underwent the treatment. The science courses typically employ collaborative small groups that are similar to the groups used in the training.

Measures

Formal Thinking Ability

The Classroom Test of Scientific Reasoning (multiple-choice version, revised edition, August 2000) was used to measure formal thinking ability (Lawson, 1978). The group-administered test is based on Piaget's formal reasoning skills; it measures the identification and control of variables, correlational reasoning, probabilistic reasoning, proportional reasoning, and hypothetico-deductive reasoning. Validity of the original test has been established by several studies (e. g., Lawson, 1978; 1992; Lawson, Baker, DiDonato, Verdi, & Johnson, 1993).

This instrument has eleven paired multiple-choice questions and two single multiple-choice questions. The paired multiple-choice questions require students to respond to a question or make a prediction and then select an explanation for their response. For example, when given narrow and wide cylinders with equally spaced marks on them and data to determine the proportionality constant between the two cylinders, the student must select in the first question how high the liquid will be in the narrow cylinder if the wide cylinder is filled to a specific line. In the corresponding paired question, the student must select an answer that demonstrates that they determined the correct answer because they determined the correct proportionality between the two cylinders.

Face validity was established with a panel of six expert judges who had 100% agreement that the instrument appeared to require concrete or formal reasoning. Convergent validity Pearson product-moment correlations between the classroom test total score and the summed level of response on two clinical interview tasks that should measure the same construct were 0.76 and statistically significant at $p < 0.001$. Factorial validity was investigated via a principal components analysis that revealed that three principal factors were extracted that accounted for 66.0% of the total variance. These factors are interpreted as being concrete reasoning, early formal reasoning, and formal reasoning. Reliability estimates were analyzed with Cronbach's Alpha coefficient at 0.86, indicating that the internal consistency of the instrument is good. The Kuder-Richardson 20 estimate of reliability was 0.78, which is adequate.

The paired multiple-choice questions allow the Classroom Test of Scientific Reasoning (CTSR) to be scored out of 13 total points where the student must correctly answer the paired questions to receive one point (11 paired questions, 2 single questions). Based on the nature of the questions and the number of each question type, scores of 0–3 were classified as concrete operational thinkers (e.g., students not able to test hypotheses involving observable causal agents). Scores of 4–6 were classified as early-transitional thinkers (e.g., students inconsistently able to test hypotheses involving observable causal agents). Scores of 7-10 were classified as transitional thinkers (e.g., students consistently able to test hypotheses involving observable causal agents). And scores of 11–13 were classified as formal operational thinkers (e.g., students able to test hypotheses involving unobservable entities). Only students in the concrete operational group were selected for the study.

Intelligence

The Raven Progressive Matrices (Raven, Raven, & Court, 1998), a thoroughly researched, 60-item instrument with well-documented reliability and predictive validity, provides a series of non-verbal tests that measure intelligence.

Comprehensive investigations have been conducted on the Raven Progressive Matrices (RPM) by numerous researchers such as Carpenter, Just, and Shell (1990), among others, verifying its psychometric properties. Banks and Sinha (1951) report the RPM's split-half reliability as 0.86 and Kuder-Richardson Formula 20 reliability as 0.91. Stinissen (1956) found the RPM's test-restest reliability ranged from 0.78 to 0.89. First released in 1938, the RPM has clinical validity as one of the most widely used measures of differences in cognitive ability (Deshon, Chan, & Weissbein, 1995). Earlier critiques of the RPM included its lack of United States norms at the time. However, US norms are now available (Raven, Raven, & Court, 1998). Other critics point out that this measure appears to measure multiple constructs such as problem-solving and spatial ability (Ackerman & Kanfer, 1993), and underlying constructs and strategies can improve performance on the test (Deshon, Chan, & Wiessbien, 1995). The non-verbal nature of the items in the RPM appears, on the face, to measure problem-solving ability. However, extensive factor analyses of the instrument suggest that the test measures one underlying construct, the Spearman *g*, a well-established construct reflecting higher-order cognitive ability (Deshon, Chan, & Weissbien, 1995). In fact, RPM results from American students (mean age = 11.2) yielded a 0.748 factor loading on general intelligence (Zagar, Arbit, & Friedland, 1980). The RPM is considered by many as a measure of intelligence due to its predictive validity of this score in relation to other intelligence tests (Haier, White, & Alkire, 2003). Burke (1958) examined the concurrent validity of the RPM and reported it correlates well with both the Stanford-Benet Intelligence Scales (0.41-0.86) and Wechsler Intelligence Scales (0.57-0.80).

The printed form of the test is designed as an individual or group test and is suitable for children above 6 years of age and for adults. Each problem consists of a design or “matrix” from which a piece has been removed. The test taker has to examine the matrix and decide which of the pieces provided below the incomplete matrix is the correct one to complete it. A testee indicates her choice by writing down the piece she selects on an answer sheet. There are five sets of problems and each set develops a different theme. The initial tests in each set are simple so the student can learn how the test works. As the tests progress they become more difficult. The order that they are presented provides the necessary training. The test takers intelligence can then be classified according to where their score falls on a percentile scale. Each test, if correctly answered, counts as one point for a maximum of sixty points. The classification system is described in Table 3.1.

Table 3.1 Raven Progressive Matrices Scoring (Raven, Raven, & Court, 1998)

Grade	Description
I	"Intellectually superior", a student whose score lies at or above the 95 percentile score for testees of their own age group
II	"Definitely above average", a student's score lies at or above the 75 percentile score.
III	"Mentally average", a student's score lies between the 75 and 25 percentile scores.
IV	"Definitely below average", a student's score lies at or below the 25 percentile score
V	"Intellectually defective", a student's score lies at or below the 5 percentile score of their age group

Statistical Analysis

Descriptive statistics will be computed for each measure. The Mann-Whitney U-test, the non-parametric statistical equivalent of the independent samples *t*-test for interval scale data, was used to compare the ordinal skill levels of the CTSR between the control and treatment subjects. This test compares the differences in distributions of scores instead of differences in average scores between groups. The U-test rank orders the data and determines the number of times a score from one group (control) precedes a score form the second group (treatment).

CHAPTER IV

RESULTS

This chapter provides a summary of the results of the measures used to determine the characteristics of the subjects before and as a result of the formal thinking skill intervention. The equivalency of the control group to the treatment group is also established.

Descriptive Statistics

Subject Equivalency

As described in the methodology, the treatment and control subjects for the study were selected to insure that they were equivalent in age, gender, scientific reasoning ability, and intelligence. Every subject except three began the study as a concrete thinker and was measured as mentally average for their age. Three of the 16-year-old subjects from the junior year chemistry course at BSHS did not begin the study as concrete thinkers due to a mix-up in testing. All of the students in the chemistry course had their thinking skills initially tested using an online thinking skill test (Monteyne, 2004) that was later found to be working improperly. From the results of the malfunctioning test the concrete thinkers ($n = 5$) were selected. The five subjects were retested using the CTSR, two of the subjects were found to be transitional thinkers and one of the subjects was an early-transitional thinker. The remaining two 16-year-old subjects were concrete operational thinkers. All five of the 16-year-old subjects were found to be mentally average for their age.

The small amount of subjects does not allow statistical comparisons in most cases. The comparisons are described below. The only statistics that were run were to compare the control students as a group to the treatment students as a group.

Subject Attrition

One treatment subject was unable to attend four of the intervention sessions due to a family vacation. That subject was removed from the study. All remaining subjects were available for all of the testing and interventions.

Pre-Treatment Measures

A summary of the results of the subjects' formal thinking skills, measured by the Classroom Test of Scientific Reasoning (CTSR) (multiple-choice version, revised edition, August 2000), before the treatment began, appears in Table 4.1. The Treatment subjects are highlighted in gray. The CTSR measures students thinking ability by testing five different formal thinking skills: (1) proportional reasoning, (2) the ability to indentify and control variables, (3) correlational reasoning, (4) probabilistic reasoning, and (5) hypothetico-deductive reasoning. The instrument also measures two concrete operational thinking skills: conservation of mass and conservation of volume. The 24-item exam has eleven paired multiple-choice questions and two single multiple-choice questions. The paired multiple-choice questions require students to respond to a question or make a prediction and then select an explanation for their response. The CTSR was scored out of 13 total points where the student must correctly answer the paired questions to receive one point (11 paired questions, 2 single questions). A summary of the results of the CTSR when scored using the paired scoring approach appears in Table 4.1 with the treatment subjects highlighted in gray. A score between 0–3 is classified as concrete operational thinkers. Scores of 4–6 are classified as early-transitional thinkers. Scores of 7-10 are classified as transitional thinkers, and scores of 11-13 are classified as formal operational thinkers. Only students in the concrete operational group were selected for the study.

Table 4.1 Summary of Pre-test CTSR Statistics

Subject	Age	Gender	CTSR Score (13)
A-10-F-C	10	F	1
B-10-F-T	10	F	2
C-10-M-C	10	M	2
D-10-M-T	10	M	2
E-10-M-C	10	M	3
F-11-F-T	11	F	3
G-11-F-C	11	F	1
H-11-F-T	11	F	3
I-11-M-C	11	M	3
J-11-M-T	11	M	2
K-12-F-C	12	F	3
L-12-F-T	12	F	2
M-12-M-C	12	M	1
N-12-M-T	12	M	3
O-13-F-C	13	F	1
P-13-F-T	13	F	2
Q-13-F-T	13	F	3
R-13-M-C	13	M	3
S-13-M-T	13	M	1
T-14-F-C	14	F	3
U-14-F-T	14	F	2
V-14-M-C	14	M	2
W-14-M-T	14	M	2
X-15-F-C	15	F	3
Y-15-F-T	15	F	3
Z-15-M-C	15	M	2
AA-15-M-T	15	M	3
BB-16-F-C[a]	16	F	6[a]
CC-16-F-T[a]	16	F	7[a]
DD-16-F-T	16	F	2
EE-16-M-C	16	M	2
FF-16-M-T[a]	16	M	5[a]

[a]These subjects did not begin as concrete operational thinkers

Table 4.2 summarizes each subject's performance with respect to their individual thinking skills as measured by the CTSR before treatment.

Table 4.2 Summary of Subject Pre-test Performance on Thinking Skills Measured by the CTSR

Subject	Thinking Skill Mastery						
	Conservation of Mass	Conservation of Volume	Proportional reasoning	Control of variable	Correlational reasoning	Probability reasoning	Hypothetic-deductive reasoning
A-10-F-C	yes	no	no	no	no	no	no
B-10-F-T	yes	no	no	no	no	no	no
C-10-M-C	yes	no	no	no	no	no	no
D-10-M-T	yes	yes	no	no	no	no	no
E-10-M-C	yes	yes	no	no	no	no	no
F-11-F-T	yes	yes	no	no	no	no	no
G-11-F-C	no	no	no	no	no	no	no
H-11-F-T	yes	yes	no	no	no	no	no
I-11-M-C	yes	yes	no	no	no	no	no
J-11-M-T	yes	yes	no	no	no	no	no
K-12-F-C	no	no	no	yes	no	no	no
L-12-F-T	yes	no	no	no	no	no	no
M-12-M-C	yes	no	no	no	no	no	no
N-12-M-T	yes	no	no	no	no	no	no
O-13-F-C	yes	no	no	no	no	no	no
P-13-F-T	no	yes	no	no	no	no	no
Q-13-F-T	yes	no	no	yes	no	no	no
R-13-M-C	yes	yes	no	yes	no	no	no
S-13-M-T	yes	no	no	no	no	no	no
T-14-F-C	yes	no	no	no	no	yes	no
U-14-F-T	yes	yes	no	no	no	no	no
V-14-M-C	yes	yes	no	no	no	no	no
W-14-M-T	yes	no	no	no	no	no	no
X-15-F-C	yes	yes	no	no	no	no	no
Y-15-F-T	yes	no	no	no	no	no	no
Z-15-M-C	yes	no	no	no	no	no	no
AA-15-M-T	yes	no	no	no	no	no	no
BB-16-F-C[a]	yes	yes	no	yes	no	no	no
CC-16-F-T[a]	yes	yes	no	yes	no	yes	no
DD-16-F-T	yes	no	no	no	no	no	no
EE-16-M-C	yes	yes	no	no	no	no	no
FF-16-M-T[a]	yes	yes	no	no	no	no	no

[a]These subjects did not begin as concrete operational thinkers

The subjects selected for the study were also matched according to intelligence by age using the Raven's Progressive Matrices instrument (RPM) (Raven, Raven,

& Court, 1998). A summary of the results of RPM for each subject before treatment began appears in Table 4.3.

Table 4.3 Summary of Pre-test RPM Statistics

Subject	Age	Gender	RPM Score (60)
A-10-F-C	10	F	37
B-10-F-T	10	F	33
C-10-M-C	10	M	40
D-10-M-T	10	M	39
E-10-M-C	10	M	40
F-11-F-T	11	F	42
G-11-F-C	11	F	43
H-11-F-T	11	F	44
I-11-M-C	11	M	46
J-11-M-T	11	M	44
K-12-F-C	12	F	44
L-12-F-T	12	F	41
M-12-M-C	12	M	42
N-12-M-T	12	M	46
O-13-F-C	13	F	42
P-13-F-T	13	F	44
Q-13-F-T	13	F	46
R-13-M-C	13	M	46
S-13-M-T	13	M	42
T-14-F-C	14	F	48
U-14-F-T	14	F	46
V-14-M-C	14	M	48
W-14-M-T	14	M	44
X-15-F-C	15	F	44
Y-15-F-T	15	F	40
Z-15-M-C	15	M	45
AA-15-M-T	15	M	47
BB-16-F-C[a]	16	F	50[a]
CC-16-F-T[a]	16	F	50[a]
DD-16-F-T	16	F	48
EE-16-M-C	16	M	44
FF-16-M-T[a]	16	M	49[a]

[a]These subjects did not begin as concrete operational thinkers

A summary of each subject's CTSR and RPM scores appears in Table 4.4.

Table 4.4 Summaries of Pre-test CTSR and RPM Statistics

Subject	Age	Gender	CTSR (13)	RPM Score (60)
A-10-F-C	10	F	1	37
B-10-F-T	10	F	2	33
C-10-M-C	10	M	2	40
D-10-M-T	10	M	2	39
E-10-M-C	10	M	3	40
F-11-F-T	11	F	3	42
G-11-F-C	11	F	1	43
H-11-F-T	11	F	3	44
I-11-M-C	11	M	3	46
J-11-M-T	11	M	2	44
K-12-F-C	12	F	3	44
L-12-F-T	12	F	2	41
M-12-M-C	12	M	1	42
N-12-M-T	12	M	3	46
O-13-F-C	13	F	1	42
P-13-F-T	13	F	2	44
Q-13-F-T	13	F	3	46
R-13-M-C	13	M	3	46
S-13-M-T	13	M	1	42
T-14-F-C	14	F	3	48
U-14-F-T	14	F	2	46
V-14-M-C	14	M	2	48
W-14-M-T	14	M	2	44
X-15-F-C	15	F	3	44
Y-15-F-T	15	F	3	40
Z-15-M-C	15	M	2	45
AA-15-M-T	15	M	3	47
BB-16-F-C[a]	16	F	6[a]	50[a]
CC-16-F-T[a]	16	F	7[a]	50[a]
DD-16-F-T	16	F	2	48
EE-16-M-C	16	M	2	44
FF-16-M-T[a]	16	M	5[a]	49[a]

[a]These subjects did not begin as concrete operational thinkers

Causal-Comparative Statistics

Post-Treatment Measures

A summary of the results of the subjects' formal thinking skills, measured by the CTSR after the treatment was completed, appears in Table 4.5. The Treatment subjects are highlighted in gray. The instrument consists of 24 questions as described in Chapter III and was scored using the paired question scoring method which has a maximum score of 13 points.

Table 4.5 Summary of Post-test CTSR Statistics

Subject	Age	Gender	CTSR Score (13)
A-10-F-C	10	F	2
B-10-F-T	10	F	4
C-10-M-C	10	M	3
D-10-M-T	10	M	2
E-10-M-C	10	M	3
F-11-F-T	11	F	5
G-11-F-C	11	F	0
H-11-F-T	11	F	6
I-11-M-C	11	M	3
J-11-M-T	11	M	2
K-12-F-C	12	F	3
L-12-F-T	12	F	2
M-12-M-C	12	M	2
N-12-M-T	12	M	6
O-13-F-C	13	F	2
P-13-F-T	13	F	3
Q-13-F-T	13	F	4
R-13-M-C	13	M	3
S-13-M-T	13	M	3
T-14-F-C	14	F	4
U-14-F-T	14	F	5
V-14-M-C	14	M	3
W-14-M-T	14	M	3
X-15-F-C	15	F	3
Y-15-F-T	15	F	2
Z-15-M-C	15	M	4
AA-15-M-T	15	M	4
BB-16-F-C[a]	16	F	6[a]
CC-16-F-T[a]	16	F	9[a]
DD-16-F-T	16	F	7
EE-16-M-C	16	M	2
FF-16-M-T[a]	16	M	5[a]

[a]These subjects did not begin as concrete operational thinkers

Table 4.6 summarizes each subject's performance with respect to their individual thinking skills as measured by the CTSR after the treatment.

Table 4.6 Summary of Subject Post-test Performance on Thinking Skills Measured by the CTSR

Subject	Thinking Skill Mastery						
	Conser-vation Mass	Conser-vation Volume	Propor-tional reasoning	Control of variable	Correla-tional reasoning	Proba-bility reasoning	Hypothetico-deductive reasoning
A-10-F-C	yes	no	no	no	no	no	no
B-10-F-T	yes	no	no	no	no	no	no
C-10-M-C	yes	no	no	no	no	no	no
D-10-M-T	yes	yes	no	no	no	no	no
E-10-M-C	yes	yes	no	no	no	no	no
F-11-F-T	yes	yes	no	no	no	yes	no
G-11-F-C	no	no	no	no	no	no	no
H-11-F-T	yes	yes	yes	yes	no	no	no
I-11-M-C	yes	yes	no	no	no	no	no
J-11-M-T	yes	yes	no	no	no	no	no
K-12-F-C	no	no	no	yes	no	no	no
L-12-F-T	yes	no	no	no	no	no	no
M-12-M-C	yes	no	no	no	no	no	no
N-12-M-T	yes	no	yes	yes	no	no	no
O-13-F-C	yes	no	no	no	no	no	no
P-13-F-T	no	yes	no	yes	no	no	no
Q-13-F-T	yes	no	no	yes	no	no	no
R-13-M-C	yes	yes	no	yes	no	no	no
S-13-M-T	yes	no	no	yes	no	no	no
T-14-F-C	yes	no	no	no	no	yes	no
U-14-F-T	yes	yes	yes	yes	no	no	no
V-14-M-C	yes	yes	no	no	no	no	no
W-14-M-T	yes	no	no	yes	no	no	no
X-15-F-C	yes	yes	no	no	no	no	no
Y-15-F-T	yes	no	no	no	no	no	no
Z-15-M-C	yes	no	no	no	no	no	no
AA-15-M-T	yes	no	no	yes	no	no	no
BB-16-F-C[a]	yes	yes	no	yes	no	no	no
CC-16-F-T[a]	yes	yes	yes	yes	yes	yes	no
DD-16-F-T	yes	no	no	yes	no	yes	no
EE-16-M-C	yes	yes	no	no	no	no	no
FF-16-M-T[a]	yes	yes	no	yes	no	yes	no

[a]These subjects did not begin as concrete operational thinkers

A summary of the results of RPM for each subject after the treatment was completed appears in Table 4.7.

Table 4.7 Summary of Post-test RPM Statistics

Subject	Age	Gender	RPM Score (60)
A-10-F-C	10	F	41
B-10-F-T	10	F	45
C-10-M-C	10	M	39
D-10-M-T	10	M	45
E-10-M-C	10	M	45
F-11-F-T	11	F	46
G-11-F-C	11	F	45
H-11-F-T	11	F	50
I-11-M-C	11	M	46
J-11-M-T	11	M	45
K-12-F-C	12	F	42
L-12-F-T	12	F	42
M-12-M-C	12	M	44
N-12-M-T	12	M	47
O-13-F-C	13	F	44
P-13-F-T	13	F	49
Q-13-F-T	13	F	46
R-13-M-C	13	M	45
S-13-M-T	13	M	48
T-14-F-C	14	F	49
U-14-F-T	14	F	44
V-14-M-C	14	M	50
W-14-M-T	14	M	49
X-15-F-C	15	F	44
Y-15-F-T	15	F	45
Z-15-M-C	15	M	46
AA-15-M-T	15	M	46
BB-16-F-C[a]	16	F	50[a]
CC-16-F-T[a]	16	F	51[a]
DD-16-F-T	16	F	49
EE-16-M-C	16	M	44
FF-16-M-T[a]	16	M	50[a]

[a]These subjects did not begin as concrete operational thinkers

Pre-Treatment/Post-Treatment Comparison Statistics

A summary of the results of the subjects' formal thinking skills measured by the CTSR both before and after the treatment was completed, appears in Table 4.8.

The Treatment subjects are highlighted in gray. All subjects except BB-16-F-C, CC-16-F-T, FF-16-M-T began as concrete operational thinkers. Subject CC-16-F-T began the study as a transitional thinker, and subjects BB-16-F-C and FF-16-M-T began the study as early-transitional thinkers.

Table 4.8 Summary of Pre-treatment/Post-treatment Comparison of CTSR Statistics

Subject	Pre-Treatment CTSR (13)	Post-Treatment CTSR (13)	Change	Thinking Skill Classification
A-10-F-C	1	2	+1	concrete
B-10-F-T	2	4	+2	early-transitional
C-10-M-C	2	3	+1	concrete
D-10-M-T	2	2	–	concrete
E-10-M-C	3	3	–	concrete
F-11-F-T	3	5	+2	early-transitional
G-11-F-C	1	0	–1	concrete
H-11-F-T	3	6	+3	early-transitional
I-11-M-C	3	3	–	concrete
J-11-M-T	2	2	–	concrete
K-12-F-C	3	3	–	concrete
L-12-F-T	2	2	–	concrete
M-12-M-C	1	2	+1	concrete
N-12-M-T	3	6	+3	early-transitional
O-13-F-C	1	2	+1	concrete
P-13-F-T	2	3	+1	concrete
Q-13-F-T	3	4	+1	early-transitional
R-13-M-C	3	3	–	concrete
S-13-M-T	1	3	+2	concrete
T-14-F-C	3	4	+1	early-transitional
U-14-F-T	2	5	+3	early-transitional
V-14-M-C	2	3	+1	concrete
W-14-M-T	2	3	+1	concrete
X-15-F-C	3	3	–	concrete
Y-15-F-T	3	2	–1	concrete
Z-15-M-C	2	4	+2	early-transitional
AA-15-M-T	3	4	+1	early-transitional
BB-16-F-C[a]	6[a]	6[a]	–	early-transitional
CC-16-F-T[a]	7[a]	9[a]	+2	transitional
DD-16-F-T	2	7	+5	transitional
EE-16-M-C	2	2	–	concrete
FF-16-M-T[a]	5[a]	5[a]	–	early-transitional

[a]These subjects did not begin as concrete operational thinkers

A summary of the results of the subjects' intelligence measured by the RPM both before and after the treatment was completed, appears in Table 4.9. The Treatment subjects are highlighted in gray.

Table 4.9 Summary of Pre-treatment/Post-treatment Comparison of RPM Statistics

Subject	Pre-Treatment RPM Score (60)	Post-Treatment RPM Score (60)	Change
A-10-F-C	37	41	+4
B-10-F-T	33	45	+12
C-10-M-C	40	39	–1
D-10-M-T	39	45	+6
E-10-M-C	40	45	+5
F-11-F-T	42	46	+4
G-11-F-C	43	45	+2
H-11-F-T	44	50	+6
I-11-M-C	46	46	–
J-11-M-T	44	45	+1
K-12-F-C	44	42	–2
L-12-F-T	41	42	+1
M-12-M-C	42	44	+2
N-12-M-T	46	47	+1
O-13-F-C	42	44	+2
P-13-F-T	44	49	+5
Q-13-F-T	46	46	–
R-13-M-C	46	45	–1
S-13-M-T	42	48	+6
T-14-F-C	48	49	+1
U-14-F-T	46	44	–2
V-14-M-C	48	50	+2
W-14-M-T	44	49	+5
X-15-F-C	44	44	–
Y-15-F-T	40	45	+5
Z-15-M-C	45	46	+1
AA-15-M-T	47	46	–1
BB-16-F-C[a]	50[a]	50[a]	–
CC-16-F-T[a]	50[a]	51[a]	+1
DD-16-F-T	48	49	+1
EE-16-M-C	44	44	–
FF-16-M-T[a]	49[a]	50[a]	+1

[a]These subjects did not begin as concrete operational thinkers

A summary of the pre-test and post-test scores for both the CTSR and the RPM appear in Table 4.10. This allows a convenient comparison between the two measures for each subject.

Table 4.10 Summary of CTSR and RPM Pre-test and Post-test Statistics

Subject	Age	Gender	CTSR (13)		RPM (60)	
			Pre-Test	Post-Test	Pre-Test	Post-Test
A-10-F-C	10	F	1	2	37	41
B-10-F-T	10	F	2	4	33	45
C-10-M-C	10	M	2	3	40	39
D-10-M-T	10	M	2	2	39	45
E-10-M-C	10	M	3	3	40	45
F-11-F-T	11	F	3	5	42	46
G-11-F-C	11	F	1	0	43	45
H-11-F-T	11	F	3	6	44	50
I-11-M-C	11	M	3	3	46	46
J-11-M-T	11	M	2	2	44	45
K-12-F-C	12	F	3	3	44	42
L-12-F-T	12	F	2	2	41	42
M-12-M-C	12	M	1	2	42	44
N-12-M-T	12	M	3	6	46	47
O-13-F-C	13	F	1	2	42	44
P-13-F-T	13	F	2	3	44	49
Q-13-F-T	13	F	3	4	46	46
R-13-M-C	13	M	3	3	46	45
S-13-M-T	13	M	1	3	42	48
T-14-F-C	14	F	3	4	48	49
U-14-F-T	14	F	2	5	46	44
V-14-M-C	14	M	2	3	48	50
W-14-M-T	14	M	2	3	44	49
X-15-F-C	15	F	3	3	44	44
Y-15-F-T	15	F	3	2	40	45
Z-15-M-C	15	M	2	4	45	46
AA-15-M-T	15	M	3	4	47	46
BB-16-F-C[a]	16	F	6[a]	6[a]	50[a]	50[a]
CC-16-F-T[a]	16	F	7[a]	9[a]	50[a]	51[a]
DD-16-F-T	16	F	2	7	48	49
EE-16-M-C	16	M	2	2	44	44
FF-16-M-T[a]	16	M	5[a]	5[a]	49[a]	50[a]

[a]These subjects did not begin as concrete operational thinkers

A summary of the results of each subject’s change in score from pre-treatment to post-treatment for the CTSR and the RPM appears in Table 4.11. The Treatment subjects are highlighted in gray.

Table 4.11 Summary of Pre- & Post-treatment change in CTSR & RPM Scores for Subjects

Subject	Age	Gender	CTSR (13) Change	RPM (60) Change
A-10-F-C	10	F	+1	+4
B-10-F-T	10	F	+2	+12
C-10-M-C	10	M	+1	−1
D-10-M-T	10	M	–	+6
E-10-M-C	10	M	–	+5
F-11-F-T	11	F	+2	+4
G-11-F-C	11	F	−1	+2
H-11-F-T	11	F	+3	+6
I-11-M-C	11	M	–	–
J-11-M-T	11	M	–	+1
K-12-F-C	12	F	–	−2
L-12-F-T	12	F	–	+1
M-12-M-C	12	M	+1	+2
N-12-M-T	12	M	+3	+1
O-13-F-C	13	F	+1	+2
P-13-F-T	13	F	+1	+5
Q-13-F-T	13	F	+1	–
R-13-M-C	13	M	–	−1
S-13-M-T	13	M	+2	+6
T-14-F-C	14	F	+1	+1
U-14-F-T	14	F	+3	−2
V-14-M-C	14	M	+1	+2
W-14-M-T	14	M	+1	+5
X-15-F-C	15	F	–	–
Y-15-F-T	15	F	−1	+5
Z-15-M-C	15	M	+2	+1
AA-15-M-T	15	M	+1	−1
BB-16-F-C[a]	16	F	–	–
CC-16-F-T[a]	16	F	+2	+1
DD-16-F-T	16	F	+5	+1
EE-16-M-C	16	M	–	–
FF-16-M-T[a]	16	M	–	+1

[a]These subjects did not begin as concrete operational thinkers

The thinking skills the CTSR measured include two concrete operational thinking skills the ability to conserve mass and the ability to conserve volume and five formal thinking skills: (1) proportional reasoning, (2) the ability to identify and control variables, (3) correlational reasoning, (4) probabilistic reasoning, and (5) hypothetico-deductive reasoning. Table 4.12 summarizes the thinking skills that students gained (+) or lost (–) after the treatment.

Table 4.12 Summary of Change in Subject's Thinking Skill Mastery as Measured by the CTSR

Subject	Change in Thinking Skill Mastery
A-10-F-C	–
B-10-F-T	–
C-10-M-C	–
D-10-M-T	–
E-10-M-C	–
F-11-F-T	+ Probabilistic reasoning
G-11-F-C	–
H-11-F-T	+ Proportional reasoning, + Control of variables
I-11-M-C	–
J-11-M-T	–
K-12-F-C	–
L-12-F-T	–
M-12-M-C	–
N-12-M-T	+ Proportional reasoning, + Control of variables
O-13-F-C	–
P-13-F-T	+ Control of variables
Q-13-F-T	–
R-13-M-C	–
S-13-M-T	+ Control of variables
T-14-F-C	–
U-14-F-T	+ Proportional reasoning, + Control of variables
V-14-M-C	–
W-14-M-T	+ Control of variables
X-15-F-C	–
Y-15-F-T	–
Z-15-M-C	–
AA-15-M-T	+ Control of variables
BB-16-F-C[a]	–
CC-16-F-T[a]	+ Proportional reasoning, + Correlational reasoning
DD-16-F-T	+ Control of variables, + Probabilistic reasoning
EE-16-M-C	–
FF-16-M-T[a]	+ Control of variables, + Probabilistic reasoning

[a]These subjects did not begin as concrete operational thinkers

Table 4.13 summarizes the major data obtained for each subject. The table records the changes from pre-treatment to post-treatment for the CTSR, the RPM, and the change in mastery of specific formal thinking skills.

Table 4.13 Summary of Pre-Treatment to Post-Treatment changes for CTSR, RPM, and Specific Thinking Skills

Subject	Age	Gender	CTSR (13)		RPM (60)		Thinking Skill Change
			Pre-Test	Post-Test	Pre-Test	Post-Test	
A-10-F-C	10	F	1	2	37	41	–
B-10-F-T	10	F	2	4	33	45	–
C-10-M-C	10	M	2	3	40	39	–
D-10-M-T	10	M	2	2	39	45	–
E-10-M-C	10	M	3	3	40	45	–
F-11-F-T	11	F	3	5	42	46	+ Prob[b]
G-11-F-C	11	F	1	0	43	45	–
H-11-F-T	11	F	3	6	44	50	+ Prop[c], + CV[d]
I-11-M-C	11	M	3	3	46	46	–
J-11-M-T	11	M	2	2	44	45	–
K-12-F-C	12	F	3	3	44	42	–
L-12-F-T	12	F	2	2	41	42	–
M-12-M-C	12	M	1	2	42	44	–
N-12-M-T	12	M	3	6	46	47	+ Prop[c], + CV[d]
O-13-F-C	13	F	1	2	42	44	–
P-13-F-T	13	F	2	3	44	49	+ CV[d]
Q-13-F-T	13	F	3	4	46	46	–
R-13-M-C	13	M	3	3	46	45	–
S-13-M-T	13	M	1	3	42	48	+ CV[d]
T-14-F-C	14	F	3	4	48	49	–
U-14-F-T	14	F	2	5	46	44	+ Prop[c] + CV[d]
V-14-M-C	14	M	2	3	48	50	–
W-14-M-T	14	M	2	3	44	49	+ CV[d]
X-15-F-C	15	F	3	3	44	44	–
Y-15-F-T	15	F	3	2	40	45	–
Z-15-M-C	15	M	2	4	45	46	–
AA-15-M-T	15	M	3	4	47	46	+ CV[d]
BB-16-F-C[a]	16	F	6[a]	6[a]	50[a]	50[a]	–
CC-16-F-T[a]	16	F	7[a]	9[a]	50[a]	51[a]	+ Prop[c], + Corr[e]
DD-16-F-T	16	F	2	7	48	49	+ CV[d] + Prob[b]
EE-16-M-C	16	M	2	2	44	44	–
FF-16-M-T[a]	16	M	5[a]	5[a]	49[a]	50[a]	+ CV[d], + Prob[b]

[a]These subjects did not begin as concrete operational thinkers
[b]Prob: Probabilistic reasoning
[c]Prop: Proportional reasoning
[d]CV: Control of variables
[e]Corr: Correlational reasoning

Comparison of Treatment and Control Subjects by Age and Gender

Tables 4.14-4.111 and Figures 4.1-4.28 summarize a pre-treatment/post-treatment comparison by age and gender for each age group, 10-16.

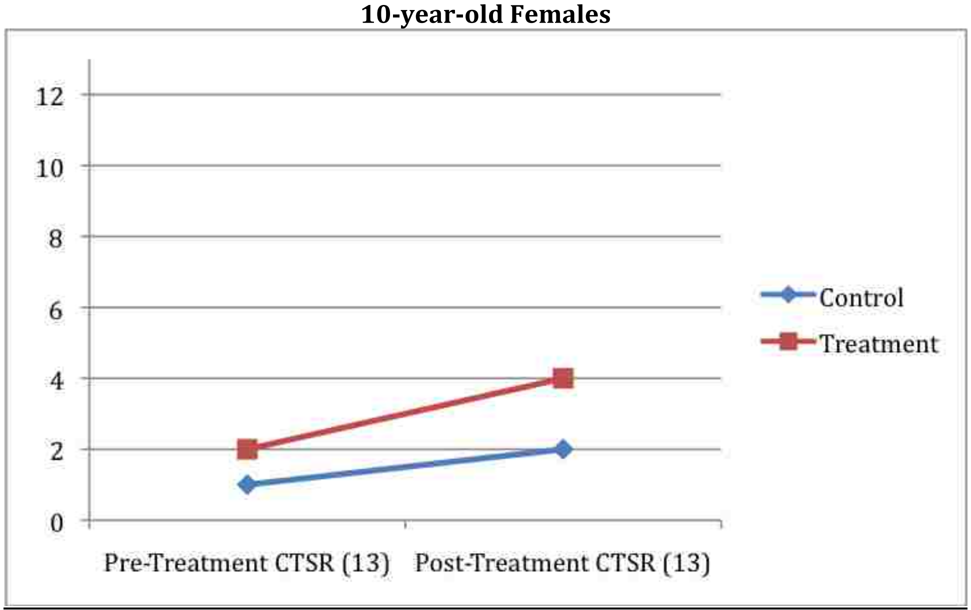
10-year-old Females

Table 4.14 and Figure 4.1 document potential changes in thinking skills during the study.

Table 4.14 Summary of Pre-treatment/Post-treatment Comparison of CTSR Statistics for 10-year-old Females

Subject	Pre-Treatment CTSR (13)	Post-Treatment CTSR (13)	Change	Thinking Skill Classification
Control	1	2	+1	concrete
Treatment	2	4	+2	early-transitional

Figure 4.1. Summary of Pre-treatment/Post-treatment Comparison of CTSR Statistics for 10-year-old Females



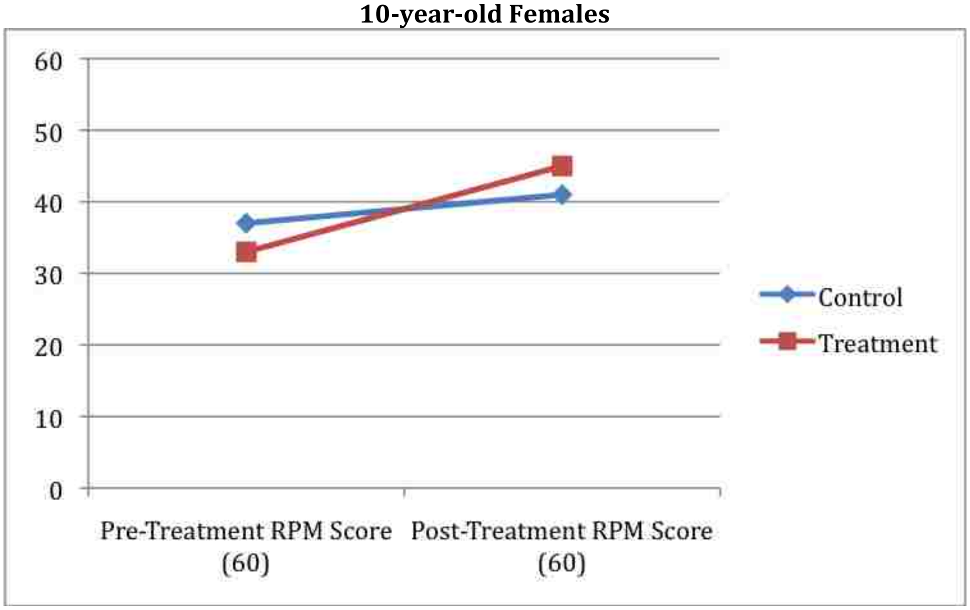
The treatment student had a slightly larger gain in their thinking skill score and moved from a concrete thinker to an early-transitional thinker. The control student remained a concrete thinker.

Table 4.15 and Figure 4.2 document potential changes in intelligence during the study.

Table 4.15 Summary of Pre-treatment/Post-treatment Comparison of RPM Statistics for 10-year-old Females

Subject	Pre-Treatment RPM Score (60)	Post-Treatment RPM Score (60)	Change
Control	37	41	+4
Treatment	33	45	+12

Figure 4.2. Summary of Pre-treatment/Post-treatment Comparison of RPM Statistics for 10-year-old Females



The treatment student had a large gain in IQ during the treatment period while the control student had a relatively moderate gain.

Table 4.16 summarizes the changes in thinking skills and intelligence during the study.

Table 4.16 Summary of Pre- & Post-treatment change in CTSR & RPM Scores for 10-year-old Females

Subject	CTSR (13) Change	RPM (60) Change
Control	+1	+4
Treatment	+2	+12

Tables 4.17-4.19 document potential changes in specific thinking skills during the study.

Table 4.17 Summary of Pre-test Performance on Thinking Skills Measured by the CTSR for 10-year-old Females

Subject	Pre-Treatment Thinking Skill Mastery						
	Conser-vation Mass	Conser-vation Volume	Propor-tional reasoning	Control of variable	Correla-tional reasoning	Proba-bility reasoning	Hypothetico-deductive reasoning
Control	yes	no	no	no	no	no	no
Treatment	yes	no	no	no	no	no	no

Table 4.18 Summary of Post-test Performance on Thinking Skills Measured by the CTSR for 10-year-old Females

Subject	Post-Treatment Thinking Skill Mastery						
	Conser-vation Mass	Conser-vation Volume	Propor-tional reasoning	Control of variable	Correla-tional reasoning	Proba-bility reasoning	Hypothetico-deductive reasoning
Control	yes	no	no	no	no	no	no
Treatment	yes	no	no	no	no	no	no

Table 4.19 Summary of Change in Thinking Skill Mastery as Measured by the CTSR for 10-year-old Females

Subject	Change in Thinking Skill Mastery
Control	–
Treatment	–

Neither the control or treatment student had any change in thinking skill mastery. Neither student had a mastery of any of the formal thinking skills.

Table 4.20 summarizes all of the data for the 10-year-old female subjects. Including their change in formal thinking skill ability, intelligence score, and mastery of specific formal thinking skills from pre-test to post-test.

Table 4.20 Summary of Pre-Treatment to Post-Treatment changes for CTSR, RPM, and Specific Thinking Skills for 10-year-old Females

Subject	Age	Gender	CTSR (13)		RPM (60)		Thinking Skill Change
			Pre-Test	Post-Test	Pre-Test	Post-Test	
Control	10	F	1	2	37	41	–
Treatment	10	F	2	4	33	45	–

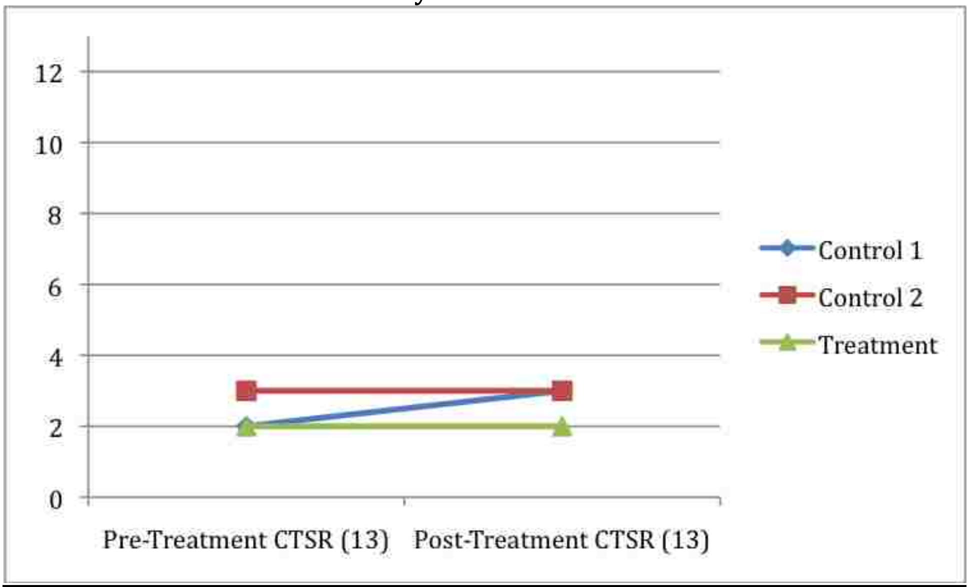
10-year-old Males

Table 4.21 and Figure 4.3 document potential changes in thinking skills during the study.

Table 4.21 Summary of Pre-treatment/Post-treatment Comparison of CTSR Statistics for 10-year-old Males

Subject	Pre-Treatment CTSR (13)	Post-Treatment CTSR (13)	Change	Thinking Skill Classification
Control 1	2	3	+1	concrete
Control 2	3	3	–	concrete
Treatment	2	2	–	concrete

Figure 4.3. Summary of Pre-treatment/Post-treatment Comparison of CTSR Statistics for 10-year-old Males



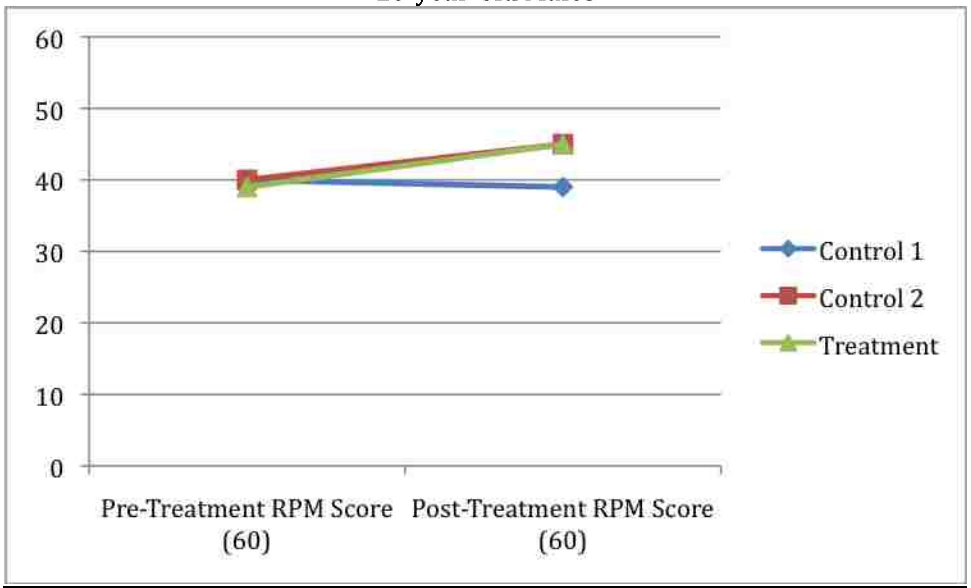
There was a slight positive change in thinking skill ability for the control 1 student and no change for the control 2 and treatment student.

Table 4.22 and Figure 4.4 document potential changes in intelligence during the study.

Table 4.22 Summary of Pre-treatment/Post-treatment Comparison of RPM Statistics for 10-year-old Males

Subject	Pre-Treatment RPM Score (60)	Post-Treatment RPM Score (60)	Change
Control 1	40	39	–1
Control 2	40	45	+5
Treatment	39	45	+6

Figure 4.4. Summary of Pre-treatment/Post-treatment Comparison of RPM Statistics for 10-year-old Males



The control 2 student and the treatment student had moderate gains in their intelligence score. The control 1 student did not have much of a change in their intelligence score.

Table 4.23 summarizes the potential changes in thinking skills and intelligence during the study.

Table 4.23 Summary of Pre- & Post-treatment change in CTSR & RPM Scores for 10-year-old Males

Subject	CTSR (13) Change	RPM (60) Change
Control 1	+1	−1
Control 2	–	+5
Treatment	–	+6

Tables 4.24-4.26 document potential changes in specific thinking skills during the study.

Table 4.24 Summary of Pre-test Performance on Thinking Skills Measured by the CTSR for 10-year-old Males

Subject	Pre-Treatment Thinking Skill Mastery						
	Conser-vation Mass	Conser-vation Volume	Propor-tional reasoning	Control of variable	Correla-tional reasoning	Proba-bility reasoning	Hypothetico-deductive reasoning
Control 1	yes	no	no	no	no	no	no
Control 2	yes	yes	no	no	no	no	no
Treatment	yes	yes	no	no	no	no	no

Table 4.25 Summary of Post-test Performance on Thinking Skills Measured by the CTSR for 10-year-old Males

Subject	Post-Treatment Thinking Skill Mastery						
	Conser-vation Mass	Conser-vation Volume	Propor-tional reasoning	Control of variable	Correla-tional reasoning	Proba-bility reasoning	Hypothetico-deductive reasoning
Control 1	yes	no	no	no	no	no	no
Control 2	yes	yes	no	no	no	no	no
Treatment	yes	yes	no	no	no	no	no

Table 4.26 Summary of Change in Thinking Skill Mastery as Measured by the CTSR for 10-year-old Males

Subject	Change in Thinking Skill Mastery
Control 1	–
Control 2	–
Treatment	–

None of the students had any change in thinking skill mastery. None of the students had a mastery of any of the formal thinking skills after the treatment.

Table 4.27 summarizes all of the data for the 10-year-old male subjects. Including their change in formal thinking skill ability, intelligence score, and mastery of specific formal thinking skills from pre-test to post-test.

Table 4.27 Summary of Pre-Treatment to Post-Treatment changes for CTSR, RPM, and Specific Thinking Skills for 10-year-old Males

Subject	CTSR (13)		RPM (60)		Thinking Skill Change
	Pre-Test	Post-Test	Pre-Test	Post-Test	
Control 1	2	3	40	39	–
Control 2	3	3	40	45	–
Treatment	2	2	39	45	–

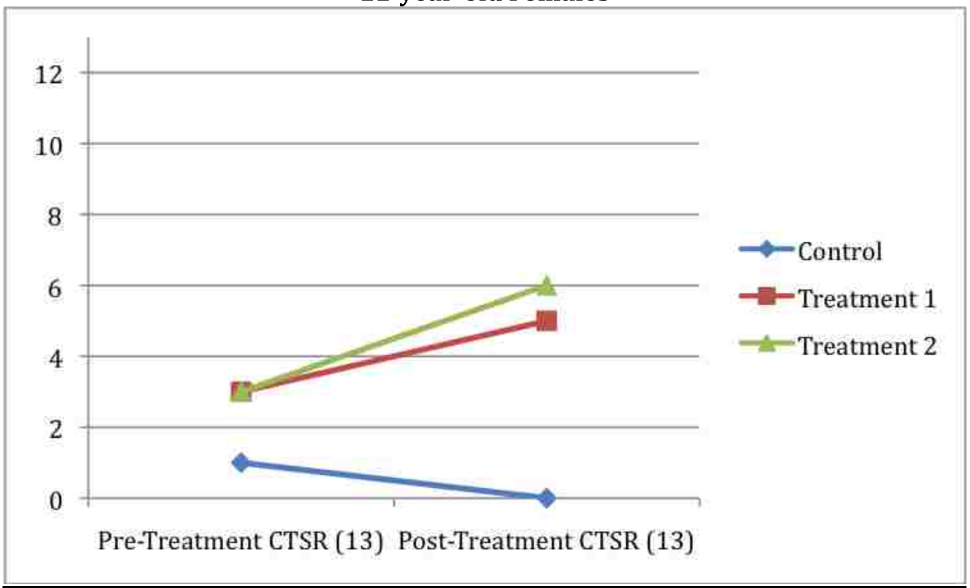
11-year-old Females

Table 4.28 and Figure 4.5 document potential changes in thinking skills during the study.

Table 4.28 Summary of Pre-treatment/Post-treatment Comparison of CTSR Statistics for 11-year-old Females

Subject	Pre-Treatment CTSR (13)	Post-Treatment CTSR (13)	Change	Thinking Skill Classification
Control	1	0	–1	concrete
Treatment 1	3	5	+2	early-transitional
Treatment 2	3	6	+3	early-transitional

Figure 4.5. Summary of Pre-treatment/Post-treatment Comparison of CTSR Statistics for 11-year-old Females



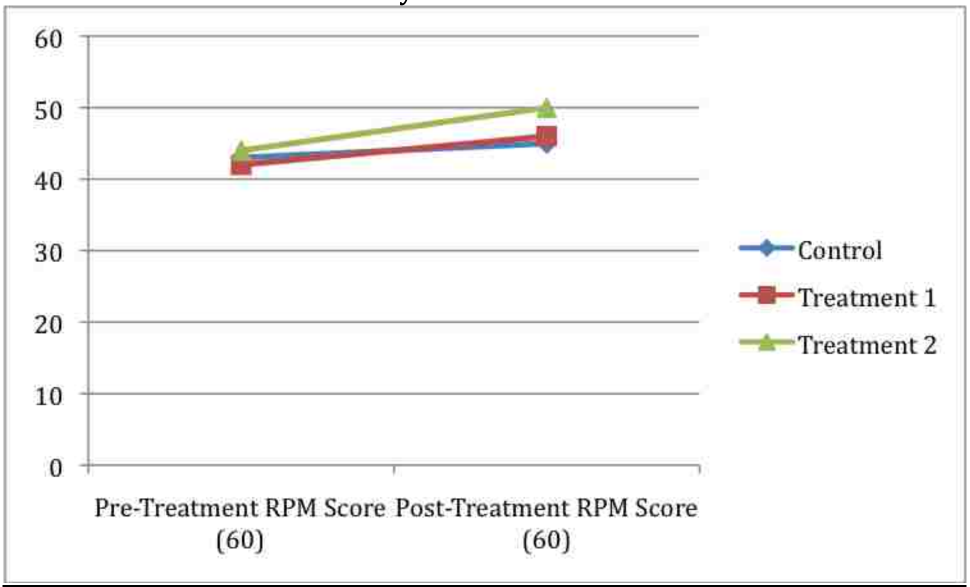
Both of the treatment students had relatively significant gains in thinking skill ability and transitioned from concrete thinkers to early-transitional thinkers after the treatment. The control student did not have a change in thinking skill ability.

Table 4.29 and Figure 4.6 document potential changes in intelligence during the study.

Table 4.29 Summary of Pre-treatment/Post-treatment Comparison of RPM Statistics for 11-year-old Females

Subject	Pre-Treatment RPM Score (60)	Post-Treatment RPM Score (60)	Change
Control	43	45	+2
Treatment 1	42	46	+4
Treatment 2	44	50	+6

Figure 4.6. Summary of Pre-treatment/Post-treatment Comparison of RPM Statistics for 11-year-old Females



The treatment students had slightly larger gains in intelligence than the control student after the treatment.

Table 4.30 summarizes the potential changes in thinking skills and intelligence during the study.

Table 4.30 Summary of Pre- & Post-treatment change in CTSR & RPM Scores for 11-year-old Females

Subject	CTSR (13) Change	RPM (60) Change
Control 1	−1	+2
Treatment 1	+2	+4
Treatment 2	+3	+6

Tables 4.31-4.33 document potential changes in specific thinking skills during the study.

Table 4.31 Summary of Pre-test Performance on Thinking Skills Measured by the CTSR for 11-year-old Females

Subject	Pre-Treatment Thinking Skill Mastery						
	Conser-vation Mass	Conser-vation Volume	Propor-tional reasoning	Control of variable	Correla-tional reasoning	Proba-bility reasoning	Hypothetic deductive reasoning
Control	no	no	no	no	no	no	no
Treatment 1	yes	yes	no	no	no	no	no
Treatment 2	yes	yes	no	no	no	no	no

Table 4.32 Summary of Post-test Performance on Thinking Skills Measured by the CTSR for 11-year-old Females

Subject	Post-Treatment Thinking Skill Mastery						
	Conser-vation Mass	Conser-vation Volume	Propor-tional reasoning	Control of variable	Correla-tional reasoning	Proba-bility reasoning	Hypothetic deductive reasoning
Control	no	no	no	no	no	no	no
Treatment 1	yes	yes	no	no	no	yes	no
Treatment 2	yes	yes	yes	yes	no	no	no

Table 4.33 Summary of Change in Thinking Skill Mastery as Measured by the CTSR for 11-year-old Females

Subject	Change in Thinking Skill Mastery
Control	–
Treatment 1	+ Probabilistic reasoning
Treatment 2	+ Proportional reasoning, + Control of variables

The control student did not have a change in thinking skill mastery. The treatment 1 student gained mastery in probabilistic reasoning, a formal thinking skill, after the treatment. The treatment 2 student gained mastery in proportional reasoning and the ability to identify and control variables, the two formal thinking skills that were taught in the treatment.

Table 4.34 summarizes all of the data for the 11-year-old female subjects. Including their change in formal thinking skill ability, intelligence score, and mastery of specific formal thinking skills from pre-test to post-test.

Table 4.34 Summary of Pre-Treatment to Post-Treatment changes for CTSR, RPM, and Specific Thinking Skills for 11-year-old Females

Subject	CTSR (13)		RPM (60)		Thinking Skill Change
	Pre-Test	Post-Test	Pre-Test	Post-Test	
Control	1	0	43	45	–
Treatment 1	3	5	42	46	+ Prob[a]
Treatment 2	3	6	44	50	+ Prop[b], + CV[c]

[a]Prob: Probabilistic reasoning
[b]Prop: Proportional reasoning
[c]CV: Control of variables

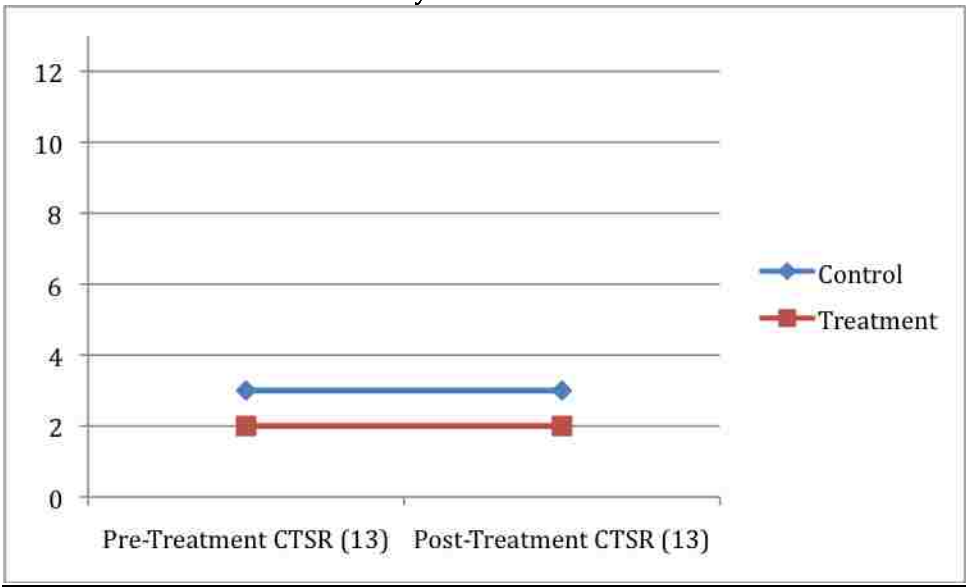
11-year-old Males

Table 4.35 and Figure 4.7 document potential changes in thinking skills during the study.

Table 4.35 Summary of Pre-treatment/Post-treatment Comparison of CTSR Statistics for 11-year-old Males

Subject	Pre-Treatment CTSR (13)	Post-Treatment CTSR (13)	Change	Thinking Skill Classification
Control	3	3	–	concrete
Treatment	2	2	–	concrete

Figure 4.7. Summary of Pre-treatment/Post-treatment Comparison of CTSR Statistics for 11-year-old Males



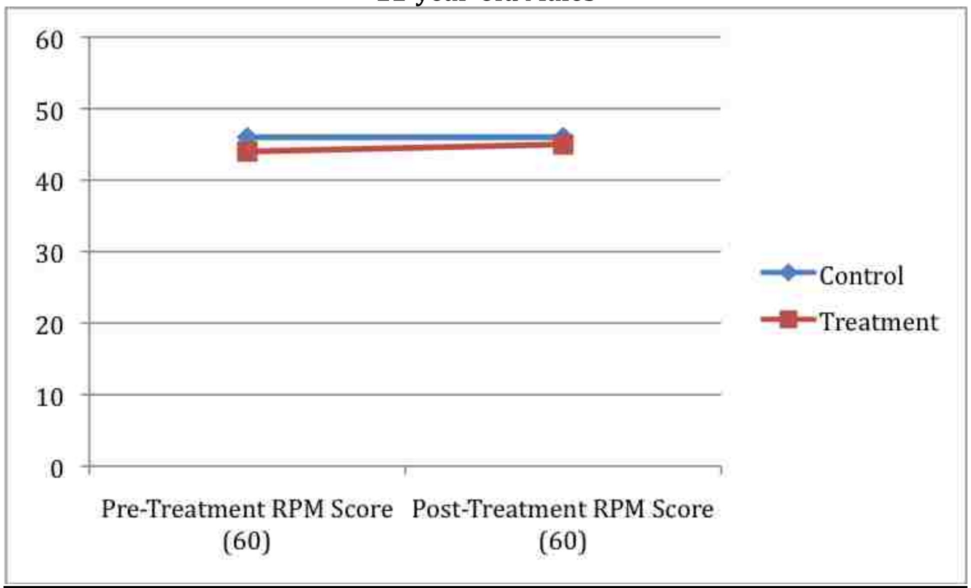
Neither the control or treatment student had a significant change in thinking skill ability after the treatment.

Table 4.36 and Figure 4.8 document potential changes in intelligence during the study.

Table 4.36 Summary of Pre-treatment/Post-treatment Comparison of RPM Statistics for 11-year-old Males

Subject	Pre-Treatment RPM Score (60)	Post-Treatment RPM Score (60)	Change
Control	46	46	–
Treatment	44	45	+1

Figure 4.8. Summary of Pre-treatment/Post-treatment Comparison of RPM Statistics for 11-year-old Males



Neither the control or treatment student had a significant change in intelligence after the treatment.

Table 4.37 summarizes the potential changes in thinking skills and intelligence during the study.

Table 4.37 Summary of Pre- & Post-treatment change in CTSR & RPM Scores for 11-year-old Males

Subject	CTSR (13) Change	RPM (60) Change
Control	–	–
Treatment	–	+1

Tables 4.38-4.40 document potential changes in specific thinking skills during the study.

Table 4.38 Summary of Pre-test Performance on Thinking Skills Measured by the CTSR for 11-year-old Males

Subject	Pre-Treatment Thinking Skill Mastery						
	Conser-vation Mass	Conser-vation Volume	Propor-tional reasoning	Control of variable	Correla-tional reasoning	Proba-bility reasoning	Hypothetico-deductive reasoning
Control	yes	yes	no	no	no	no	no
Treatment	yes	yes	no	no	no	no	no

Table 4.39 Summary of Post-test Performance on Thinking Skills Measured by the CTSR for 11-year-old Males

Subject	Post-Treatment Thinking Skill Mastery						
	Conser-vation Mass	Conser-vation Volume	Propor-tional reasoning	Control of variable	Correla-tional reasoning	Proba-bility reasoning	Hypothetico-deductive reasoning
Control	yes	yes	no	no	no	no	no
Treatment	yes	yes	no	no	no	no	no

Table 4.40. Summary of Change in Thinking Skill Mastery as Measured by the CTSR for 11-year-old Males

Subject	Change in Thinking Skill Mastery
Control	–
Treatment	–

Neither of the control or treatment student had any change in thinking skill mastery. Neither of the students had a mastery of any of the formal thinking skills before or after the treatment.

Table 4.41 summarizes all of the data for the 11-year-old male subjects. Including their change in formal thinking skill ability, intelligence score, and mastery of specific formal thinking skills from pre-test to post-test.

Table 4.41 Summary of Pre-Treatment to Post-Treatment changes for CTSR, RPM, and Specific Thinking Skills for 11-year-old Males

Subject	CTSR (13)		RPM (60)		Thinking Skill Change
	Pre-Test	Post-Test	Pre-Test	Post-Test	
Control	3	3	46	46	–
Treatment	2	2	44	45	–

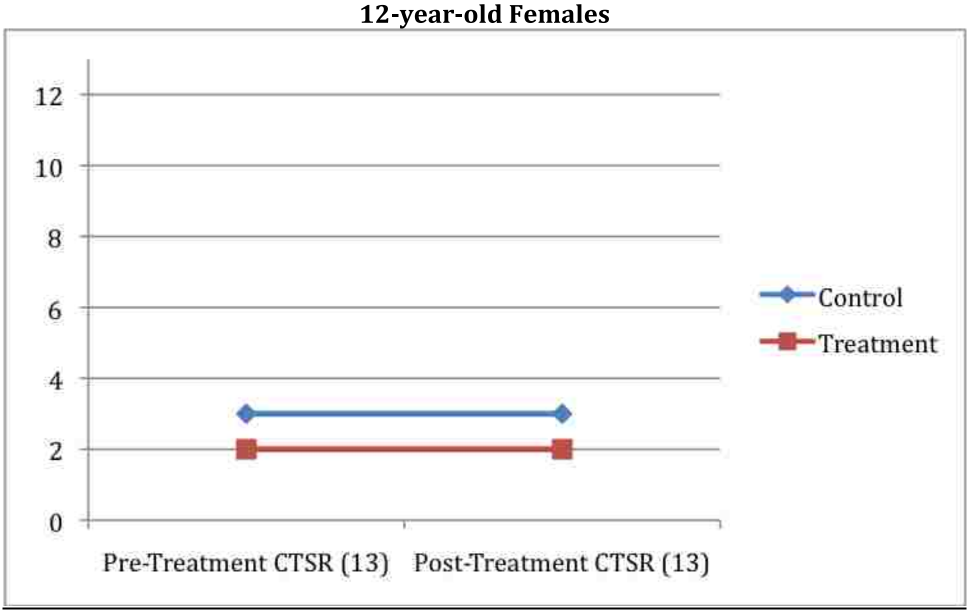
12-year-old Females

Table 4.42 and Figure 4.9 document potential changes in thinking skills during the study.

Table 4.42 Summary of Pre-treatment/Post-treatment Comparison of CTSR Statistics for 12-year-old Females

Subject	Pre-Treatment CTSR (13)	Post-Treatment CTSR (13)	Change	Thinking Skill Classification
Control	3	3	–	concrete
Treatment	2	2	–	concrete

Figure 4.9. Summary of Pre-treatment/Post-treatment Comparison of CTSR Statistics for 12-year-old Females



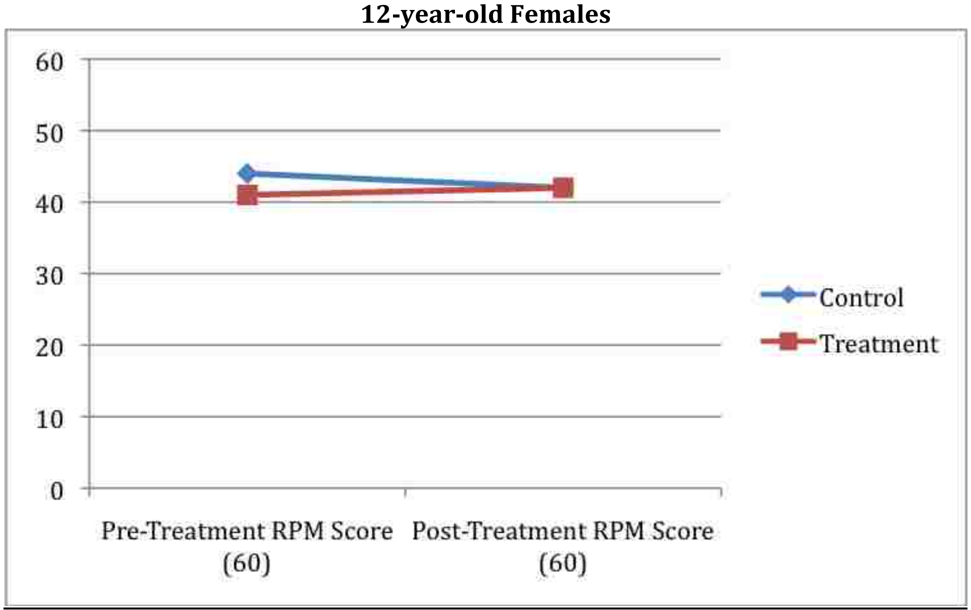
Neither the control or treatment student had a significant change in thinking skill ability after the treatment.

Table 4.43 and Figure 4.10 document potential changes in intelligence during the study.

Table 4.43 Summary of Pre-treatment/Post-treatment Comparison of RPM Statistics for 12-year-old Females

Subject	Pre-Treatment RPM Score (60)	Post-Treatment RPM Score (60)	Change
Control	44	42	–2
Treatment	41	42	+1

Figure 4.10. Summary of Pre-treatment/Post-treatment Comparison of RPM Statistics for 12-year-old Females



The control student had a small decrease on their intelligence score while the treatment student had a small gain on their intelligence score after the treatment.

Table 4.44 summarizes the potential changes in thinking skills and intelligence during the study.

Table 4.44 Summary of Pre- & Post-treatment change in CTSR & RPM Scores for 12-year-old Females

Subject	CTSR (13) Change	RPM (60) Change
Control	–	–2
Treatment	–	+1

Tables 4.45-4.47 document potential changes in specific thinking skills during the study.

Table 4.45 Summary of Pre-test Performance on Thinking Skills Measured by the CTSR for 12-year-old Females

Subject	Pre-Treatment Thinking Skill Mastery						
	Conser-vation Mass	Conser-vation Volume	Propor-tional reasoning	Control of variable	Correla-tional reasoning	Proba-bility reasoning	Hypothetico-deductive reasoning
Control	no	no	no	yes	no	no	no
Treatment	yes	no	no	no	no	no	no

Table 4.46 Summary of Post-test Performance on Thinking Skills Measured by the CTSR for 12-year-old Females

Subject	Post-Treatment Thinking Skill Mastery						
	Conser-vation Mass	Conser-vation Volume	Propor-tional reasoning	Control of variable	Correla-tional reasoning	Proba-bility reasoning	Hypothetico-deductive reasoning
Control	no	no	no	yes	no	no	no
Treatment	yes	no	no	no	no	no	no

Table 4.47 Summary of Change in Thinking Skill Mastery as Measured by the CTSR for 12-year-old Females

Subject	Change in Thinking Skill Mastery
Control	–
Treatment	–

Neither the control or treatment student had any change in thinking skill mastery. The control student may have had a mastery of the ability to identify and control variables; a formal thinking skill. The 12-year-old female control student correctly answered the control of variables question on both the pre-test and post-test of the CTSR. The treatment student did not have a mastery of any of the formal thinking skills before or after the treatment.

Table 4.48 summarizes all of the data for the 12-year-old female subjects. Including their change in formal thinking skill ability, intelligence score, and mastery of specific formal thinking skills from pre-test to post-test.

Table 4.48 Summary of Pre-Treatment to Post-Treatment changes for CTSR, RPM, and Specific Thinking Skills for 12-year-old Females

Subject	CTSR (13)		RPM (60)		Thinking Skill Change
	Pre-Test	Post-Test	Pre-Test	Post-Test	
Control	3	3	44	42	–
Treatment	2	2	41	42	–

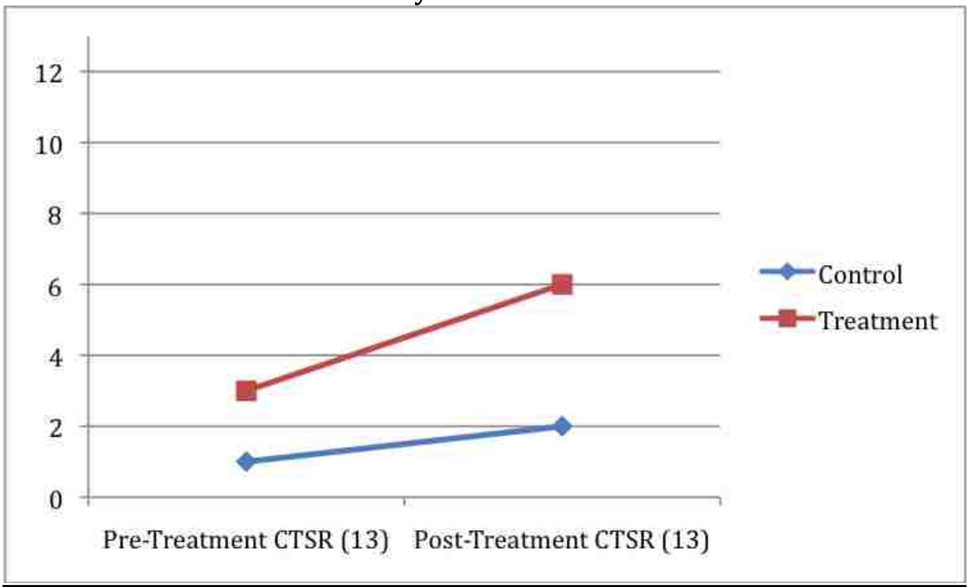
12-year-old Males

Table 4.49 and Figure 4.11 document potential changes in thinking skills during the study.

Table 4.49 Summary of Pre-treatment/Post-treatment Comparison of CTSR Statistics for 12-year-old Males

Subject	Pre-Treatment CTSR (13)	Post-Treatment CTSR (13)	Change	Thinking Skill Classification
Control	1	2	+1	concrete
Treatment	3	6	+3	early-transitional

Figure 4.11. Summary of Pre-treatment/Post-treatment Comparison of CTSR Statistics for 12-year-old Males



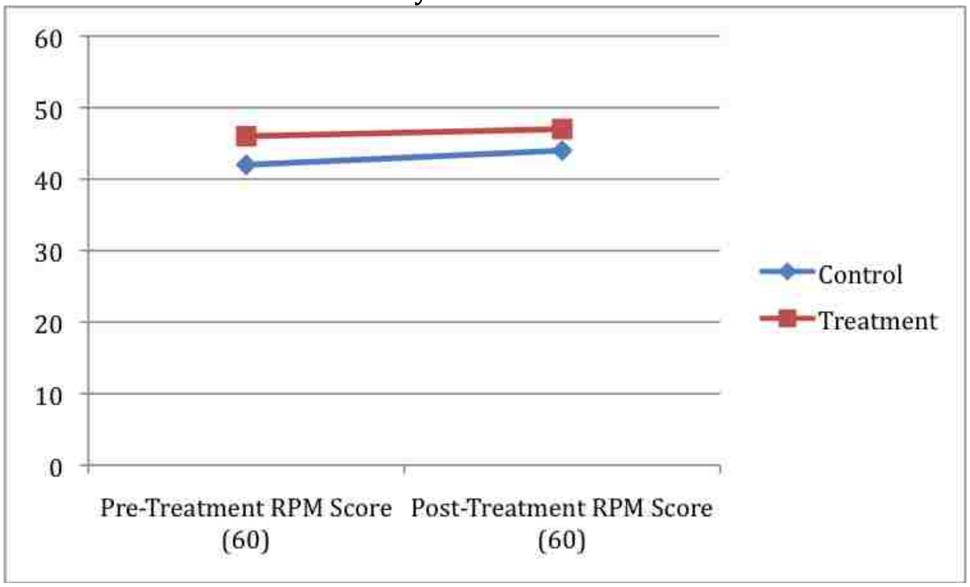
The treatment student had a relatively significant gain in thinking skill ability and transitioned from a concrete thinker to an early-transitional thinker after the treatment. The control student had a small change in thinking skill ability but remained a concrete thinker.

Table 4.50 and Figure 4.12 document potential changes in intelligence during the study.

Table 4.50 Summary of Pre-treatment/Post-treatment Comparison of RPM Statistics for 12-year-old Males

Subject	Pre-Treatment RPM Score (60)	Post-Treatment RPM Score (60)	Change
Control	42	44	+2
Treatment	46	47	+1

Figure 4.12. Summary of Pre-treatment/Post-treatment Comparison of RPM Statistics of 12-year-old Males



Both the control and the treatment student had a slight gain in intelligence after taking the post-treatment RPM exam.

Table 4.51 summarizes the potential changes in thinking skills and intelligence during the study.

Table 4.51 Summary of Pre- & Post-treatment change in CTSR & RPM Scores for 12-year-old Males

Subject	CTSR (13) Change	RPM (60) Change
Control	+1	+2
Treatment	+3	+1

Tables 4.52-4.54 document potential changes in specific thinking skills during the study.

Table 4.52 Summary of Pre-test Performance on Thinking Skills Measured by the CTSR for 12-year-old Males

Subject	Pre-Treatment Thinking Skill Mastery						
	Conser-vation Mass	Conser-vation Volume	Propor-tional reasoning	Control of variable	Correla-tional reasoning	Proba-bility reasoning	Hypothetico-deductive reasoning
Control	yes	no	no	no	no	no	no
Treatment	yes	no	no	no	no	no	no

Table 4.53 Summary of Post-test Performance on Thinking Skills Measured by the CTSR for 12-year-old Males

Subject	Post-Treatment Thinking Skill Mastery						
	Conser-vation Mass	Conser-vation Volume	Propor-tional reasoning	Control of variable	Correla-tional reasoning	Proba-bility reasoning	Hypothetico-deductive reasoning
Control	yes	no	no	no	no	no	no
Treatment	yes	no	yes	yes	no	no	no

Table 4.54 Summary of Change in Thinking Skill Mastery as Measured by the CTSR for 12-year-old Males

Subject	Change in Thinking Skill Mastery
Control	–
Treatment	+ Proportional reasoning, + Control of variables

The control student did not have a change in thinking skill mastery. The treatment student gained mastery in proportional reasoning and the ability to identify and control variables, the two formal thinking skills that were taught in the treatment.

Table 4.55 summarizes all of the data for the 12-year-old male subjects. Including their change in formal thinking skill ability, intelligence score, and mastery of specific formal thinking skills from pre-test to post-test.

Table 4.55 Summary of Pre-Treatment to Post-Treatment changes for CTSR, RPM, and Specific Thinking Skills for 12-year-old Males

Subject	CTSR (13)		RPM (60)		Thinking Skill Change
	Pre-Test	Post-Test	Pre-Test	Post-Test	
Control	1	2	42	44	–
Treatment	3	6	46	47	+ Prop[a], + CV[b]

[a]Prop: Proportional reasoning
[b]CV: Control of variables

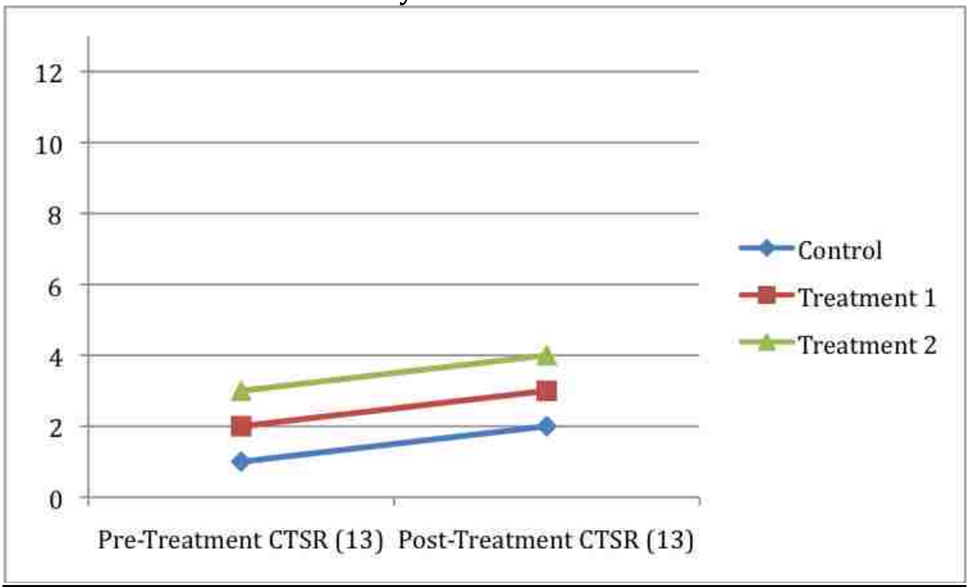
13-year-old Females

Table 4.56 and Figure 4.13 document potential changes in thinking skills during the study.

Table 4.56 Summary of Pre-treatment/Post-treatment Comparison of CTSR Statistics for 13-year-old Females

Subject	Pre-Treatment CTSR (13)	Post-Treatment CTSR (13)	Change	Thinking Skill Classification
Control	1	2	+1	concrete
Treatment 1	2	3	+1	concrete
Treatment 2	3	4	+1	early-transitional

Figure 4.13. Summary of Pre-treatment/Post-treatment Comparison of CTSR Statistics for 13-year-old Females



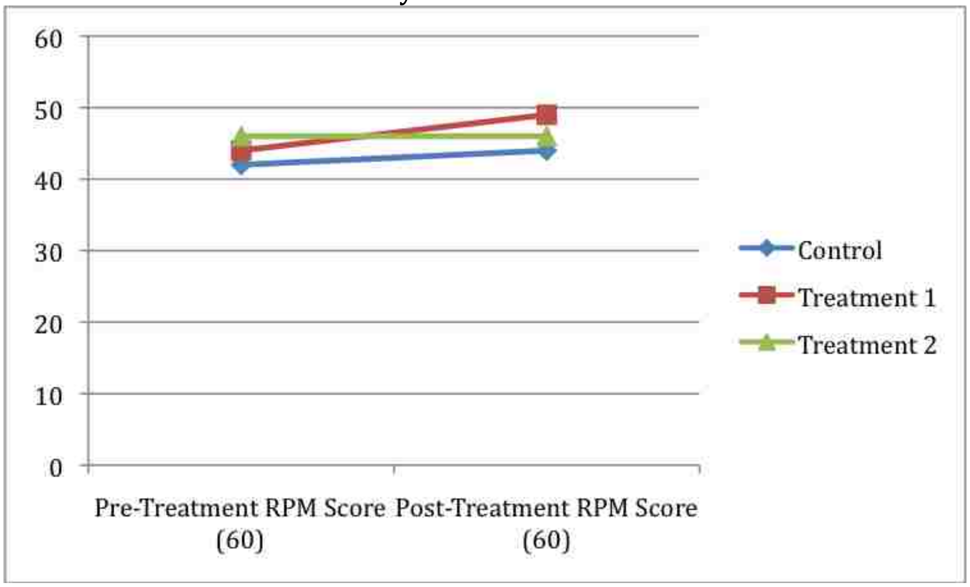
The control student and the treatment students had small gains in thinking skill ability after taking the post-treatment CTSR. The treatment 2 student moved from a concrete thinker to an early-transitional thinker.

Table 4.57 and Figure 4.14 document potential changes in intelligence during the study.

Table 4.57 Summary of Pre-treatment/Post-treatment Comparison of RPM Statistics for 13-year-old Females

Subject	Pre-Treatment RPM Score (60)	Post-Treatment RPM Score (60)	Change
Control	42	44	+2
Treatment 1	44	49	+5
Treatment 2	46	46	–

Figure 4.14. Summary of Pre-treatment/Post-treatment Comparison of RPM Statistics for 13-year-old Females



Both the control and the treatment 1 student had a slight gain in intelligence after taking the post-treatment RPM exam. The treatment 2 student did not have any change in measured intelligence.

Table 4.58 summarizes the potential changes in thinking skills and intelligence during the study.

Table 4.58 Summary of Pre- & Post-treatment change in CTSR & RPM Scores for 13-year-old Females

Subject	CTSR (13) Change	RPM (60) Change
Control	+1	+2
Treatment 1	+1	+5
Treatment 2	+1	–

Tables 4.59-4.61 document potential changes in specific thinking skills during the study.

Table 4.59 Summary of Pre-test Performance on Thinking Skills Measured by the CTSR for 13-year-old Females

Subject	Pre-Treatment Thinking Skill Mastery						
	Conser-vation Mass	Conser-vation Volume	Propor-tional reasoning	Control of variable	Correla-tional reasoning	Proba-bility reasoning	Hypothetic deductive reasoning
Control	yes	no	no	no	no	no	no
Treatment 1	no	yes	no	no	no	no	no
Treatment 2	yes	no	no	yes	no	no	no

Table 4.60 Summary of Post-test Performance on Thinking Skills Measured by the CTSR for 13-year-old Females

Subject	Post-Treatment Thinking Skill Mastery						
	Conser-vation Mass	Conser-vation Volume	Propor-tional reasoning	Control of variable	Correla-tional reasoning	Proba-bility reasoning	Hypothetic deductive reasoning
Control	yes	no	no	no	no	no	no
Treatment 1	no	yes	no	yes	no	no	no
Treatment 2	yes	no	no	yes	no	no	no

Table 4.61 Summary of in Subject's Thinking Skill Mastery as Measured by the CTSR for 13-year-old Females

Subject	Change in Thinking Skill Mastery
Control	–
Treatment 1	+ Control of variables
Treatment 2	–

The control student did not have a change in thinking skill mastery. The treatment 1 student gained mastery in the ability to identify and control variables, one of the formal thinking skills taught in the treatment. The treatment 2 student began the study with the formal thinking skill ability to identify and control of variables but did not gain any other formal thinking skills after the treatment.

Table 4.62 summarizes all of the data for the 13-year-old female subjects. Including their change in formal thinking skill ability, intelligence score, and mastery of specific formal thinking skills from pre-test to post-test.

Table 4.62 Summary of Pre-Treatment to Post-Treatment changes for CTSR, RPM, and Specific Thinking Skills for 13-year-old Females

Subject	CTSR (13)		RPM (60)		Thinking Skill Change
	Pre-Test	Post-Test	Pre-Test	Post-Test	
Control	1	2	42	44	–
Treatment 1	2	3	44	49	+ CV[a]
Treatment 2	3	4	46	46	–

[a]CV: Control of variables

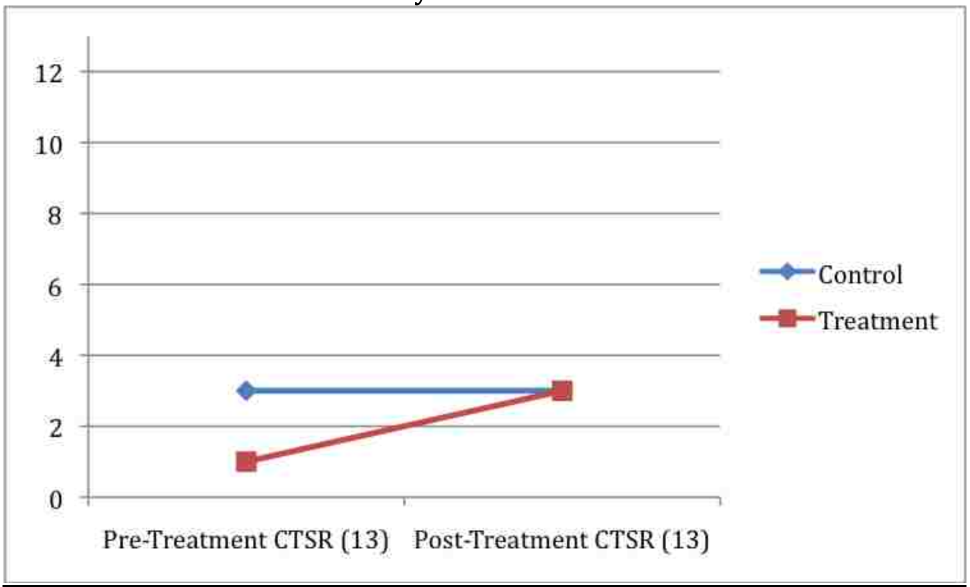
13-year-old Males

Table 4.63 and Figure 4.15 document potential changes in thinking skills during the study.

Table 4.63 Summary of Pre-treatment/Post-treatment Comparison of CTSR Statistics for 13-year-old Males

Subject	Pre-Treatment CTSR (13)	Post-Treatment CTSR (13)	Change	Thinking Skill Classification
Control	3	3	–	concrete
Treatment	1	3	+2	concrete

Figure 4.15. Summary of Pre-treatment/Post-treatment Comparison of CTSR Statistics for 13-year-old Males



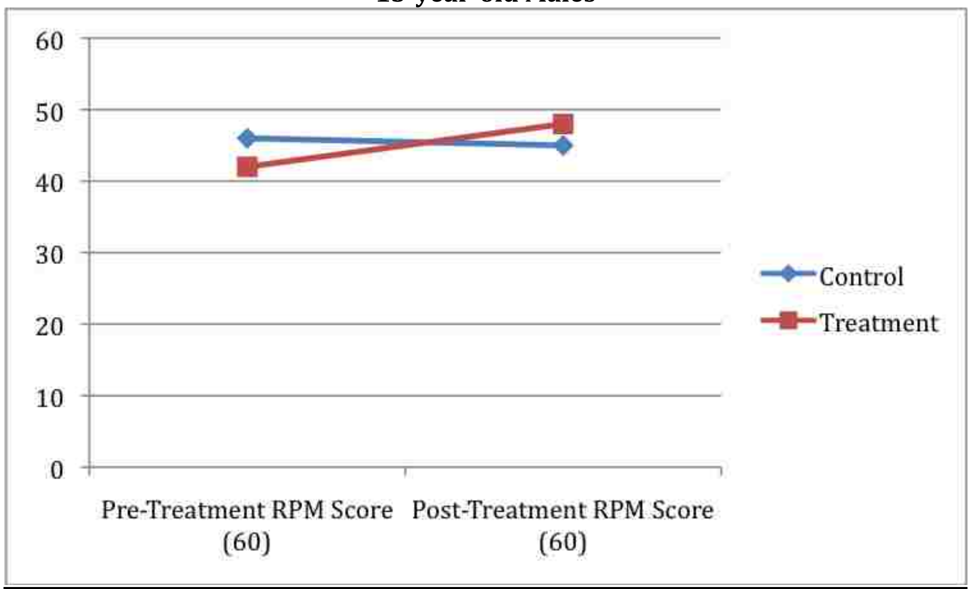
The treatment student had a moderate gain in thinking skill ability. However with the paired scoring approach the treatment student remained classified as a concrete thinker. The control student did not have a change in thinking skill ability.

Table 4.64 and Figure 4.16 document potential changes in intelligence during the study.

Table 4.64 Summary of Pre-treatment/Post-treatment Comparison of RPM Statistics for 13-year-old Males

Subject	Pre-Treatment RPM Score (60)	Post-Treatment RPM Score (60)	Change
Control	46	45	–1
Treatment	42	48	+6

Figure 4.16. Summary of Pre-treatment/Post-treatment Comparison of RPM Statistics for 13-year-old Males



The control student did not have much of a change in their intelligence score. The treatment student had a gain on their intelligence score.

Table 4.65 summarizes the potential changes in thinking skills and intelligence during the study.

Table 4.65 Summary of Pre- & Post-treatment change in CTSR & RPM Scores for 13-year-old Males

Subject	CTSR (13) Change	RPM (60) Change
Control	–	−1
Treatment	+2	+6

Tables 4.66-4.68 document potential changes in specific thinking skills during the study.

Table 4.66 Summary of Pre-test Performance on Thinking Skills Measured by the CTSR for 13-year-old Males

Subject	Pre-Treatment Thinking Skill Mastery						
	Conser-vation Mass	Conser-vation Volume	Propor-tional reasoning	Control of variable	Correla-tional reasoning	Proba-bility reasoning	Hypothetico-deductive reasoning
Control	yes	yes	no	yes	no	no	no
Treatment	yes	no	no	no	no	no	no

Table 4.67 Summary of Post-test Performance on Thinking Skills Measured by the CTSR for 13-year-old Males

Subject	Post-Treatment Thinking Skill Mastery						
	Conser-vation Mass	Conser-vation Volume	Propor-tional reasoning	Control of variable	Correla-tional reasoning	Proba-bility reasoning	Hypothetico-deductive reasoning
Control	yes	yes	no	yes	no	no	no
Treatment	yes	no	no	yes	no	no	no

Table 4.68 Summary of Change in Thinking Skill Mastery as Measured by the CTSR for 13-year-old Males

Subject	Change in Thinking Skill Mastery
Control	–
Treatment	+ Control of variables

The control student did not have a change in thinking skill mastery. The treatment student gained mastery in the ability to identify and control variables, one of the formal thinking skills that were taught in the treatment.

Table 4.69 summarizes all of the data for the 13-year-old male subjects. Including their change in formal thinking skill ability, intelligence score, and mastery of specific formal thinking skills from pre-test to post-test.

Table 4.69 Summary of Pre-Treatment to Post-Treatment changes for CTSR, RPM, and Specific Thinking Skills for 13-year-old Males

Subject	CTSR (13)		RPM (60)		Thinking Skill Change
	Pre-Test	Post-Test	Pre-Test	Post-Test	
Control	3	3	46	45	–
Treatment	1	3	42	48	+ CV[a]

[a]CV: Control of variables

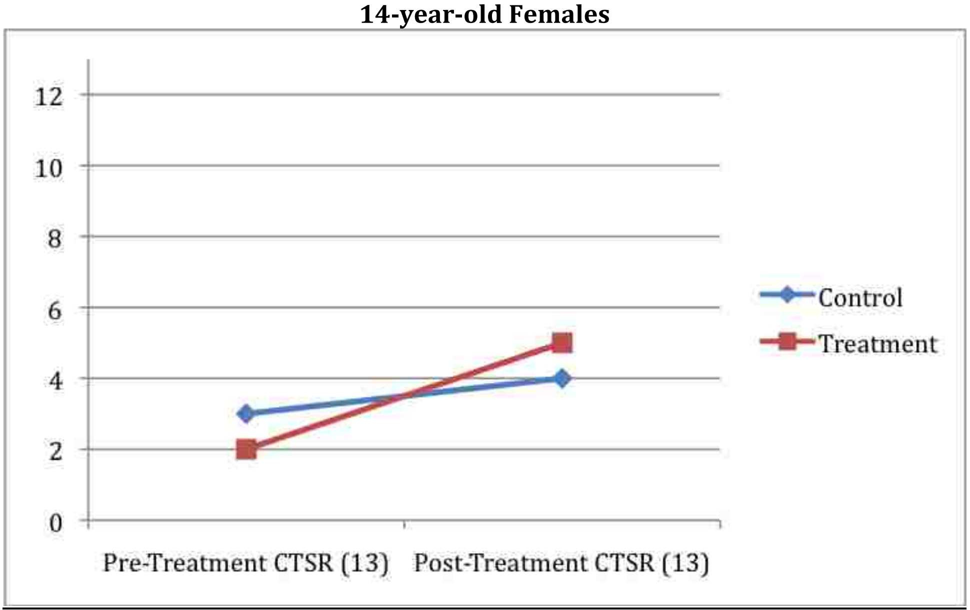
14-year-old Females

Table 4.70 and Figure 4.17 document potential changes in thinking skills during the study.

Table 4.70 Summary of Pre-treatment/Post-treatment Comparison of CTSR Statistics for 14-year-old Females

Subject	Pre-Treatment CTSR (13)	Post-Treatment CTSR (13)	Change	Thinking Skill Classification
Control	3	4	+1	early-transitional
Treatment	2	5	+3	early-transitional

Figure 4.17. Summary of Pre-treatment/Post-treatment Comparison of CTSR Statistics for 14-year-old Females



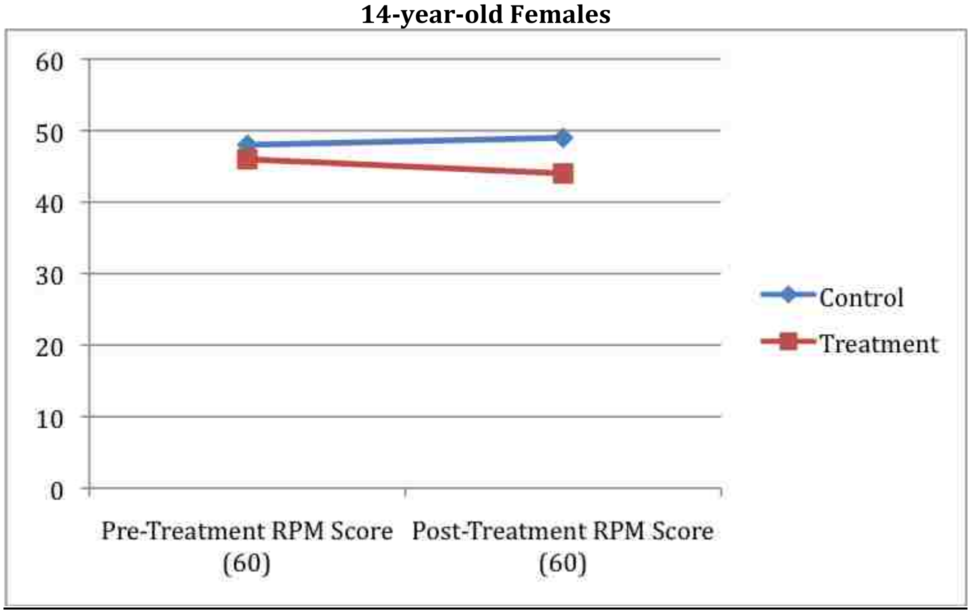
The control student had a small gain in thinking skill ability. Using the paired scoring approach the control student changed from a concrete thinker to an early-transitional thinker. The treatment student had a relatively large gain in thinking skill ability and moved from a concrete thinker to an early-transitional thinker.

Table 4.71 and Figure 4.18 document potential changes in intelligence during the study.

Table 4.71 Summary of Pre-treatment/Post-treatment Comparison of RPM Statistics for 14-year-old Females

Subject	Pre-Treatment RPM Score (60)	Post-Treatment RPM Score (60)	Change
Control	48	49	+1
Treatment	46	44	–2

Figure 4.18. Summary of Pre-treatment/Post-treatment Comparison of RPM Statistics for 14-year-old Females



The control student had a slight gain in their intelligence score. The treatment student had a small decrease on their intelligence score.

Table 4.72 summarizes the potential changes in thinking skills and intelligence during the study.

Table 4.72 Summary of Pre- & Post-treatment change in CTSR & RPM Scores for 14-year-old Females

Subject	CTSR (13) Change	RPM (60) Change
Control	+1	+1
Treatment	+3	–2

Tables 4.73-4.75 document potential changes in specific thinking skills during the study.

Table 4.73 Summary of Pre-test Performance on Thinking Skills Measured by the CTSR for 14-year-old Females

Subject	Pre-Treatment Thinking Skill Mastery						
	Conser-vation Mass	Conser-vation Volume	Propor-tional reasoning	Control of variable	Correla-tional reasoning	Proba-bility reasoning	Hypothetico-deductive reasoning
Control	yes	no	no	no	no	yes	no
Treatment	yes	yes	no	no	no	no	no

Table 4.74 Summary of Post-test Performance on Thinking Skills Measured by the CTSR for 14-year-old Females

Subject	Post-Treatment Thinking Skill Mastery						
	Conser-vation Mass	Conser-vation Volume	Propor-tional reasoning	Control of variable	Correla-tional reasoning	Proba-bility reasoning	Hypothetico-deductive reasoning
Control	yes	no	no	no	no	yes	no
Treatment	yes	yes	yes	yes	no	no	no

Table 4.75 Summary of Change in Thinking Skill Mastery as Measured by the CTSR for 14-year-old Females

Subject	Change in Thinking Skill Mastery
Control	–
Treatment	+ Proportional reasoning, + Control of variables

The control student did not have a change in thinking skill mastery. The control student had mastered probabilistic reasoning before the study began. The treatment student gained mastery in proportional reasoning and the ability to identify and control variables, the two formal thinking skills that were taught in the treatment.

Table 4.76 summarizes all of the data for the 14-year-old female subjects. Including their change in formal thinking skill ability, intelligence score, and mastery of specific formal thinking skills from pre-test to post-test.

Table 4.76 Summary of Pre-Treatment to Post-Treatment changes for CTSR, RPM, and Specific Thinking Skills for 14-year-old Females

Subject	CTSR (13)		RPM (60)		Thinking Skill Change
	Pre-Test	Post-Test	Pre-Test	Post-Test	
Control	3	4	48	49	–
Treatment	2	5	46	44	+ Prop[a] + CV[b]

[a]Prop: Proportional reasoning
[b]CV: Control of variables

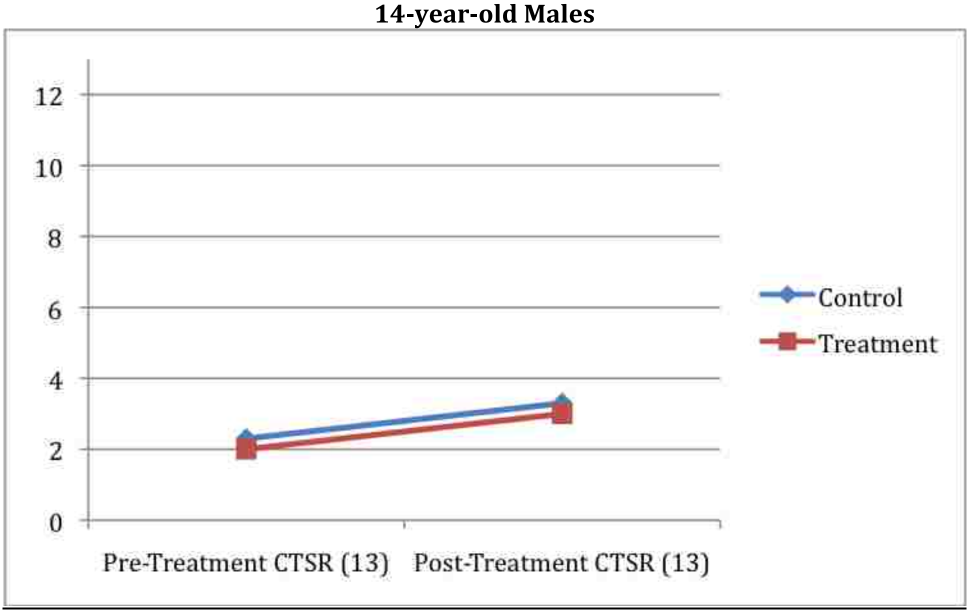
14-year-old Males

Table 4.77 and Figure 4.19 document potential changes in thinking skills during the study.

Table 4.77 Summary of Pre-treatment/Post-treatment Comparison of CTSR Statistics for 14-year-old Males

Subject	Pre-Treatment CTSR (13)	Post-Treatment CTSR (13)	Change	Thinking Skill Classification
Control	2	3	+1	concrete
Treatment	2	3	+1	concrete

Figure 4.19. Summary of Pre-treatment/Post-treatment Comparison of CTSR Statistics for 14-year-old Males



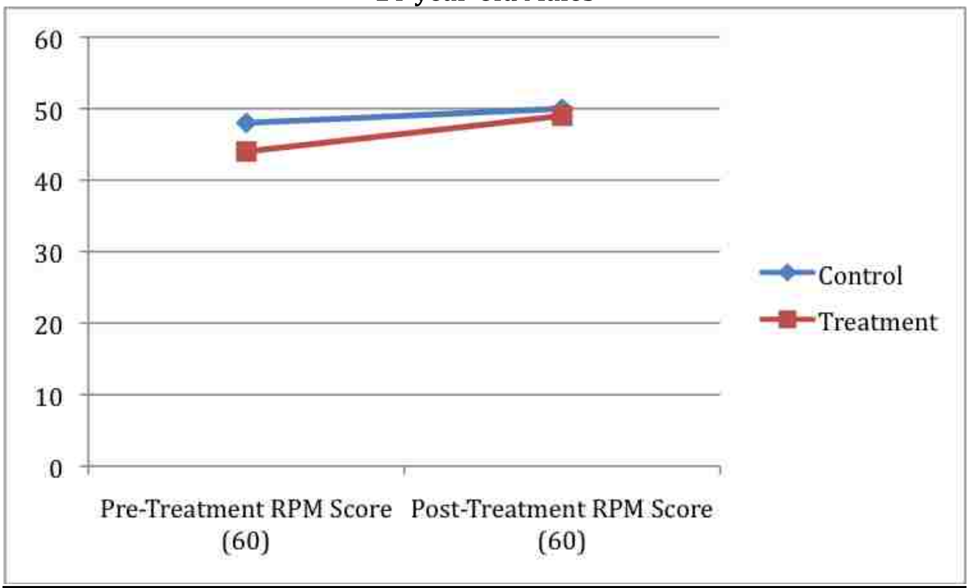
Both the control and treatment students had a small gain in thinking skill ability.

Table 4.78 and Figure 4.20 document potential changes in intelligence during the study.

Table 4.78 Summary of Pre-treatment/Post-treatment Comparison of RPM Statistics for 14-year-old Males

Subject	Pre-Treatment RPM Score (60)	Post-Treatment RPM Score (60)	Change
Control	48	50	+2
Treatment	44	49	+5

Figure 4.20. Summary of Pre-treatment/Post-treatment Comparison of RPM Statistics for 14-year-old Males



The control student had a slight gain in their intelligence score. The treatment student had a slightly larger gain on their intelligence score.

Table 4.79 summarizes the potential changes in thinking skills and intelligence during the study.

Table 4.79 Summary of Pre- & Post-treatment change in CTSR & RPM Scores for 14-year-old Males

Subject	CTSR (13) Change	RPM (60) Change
Control	+1	+2
Treatment	+1	+5

Tables 4.80-4.82 document potential changes in specific thinking skills during the study.

Table 4.80 Summary of Pre-test Performance on Thinking Skills Measured by the CTSR for 14-year-old Males

Subject	Pre-Treatment Thinking Skill Mastery						
	Conser-vation Mass	Conser-vation Volume	Propor-tional reasoning	Control of variable	Correla-tional reasoning	Proba-bility reasoning	Hypothetico-deductive reasoning
Control	yes	yes	no	no	no	no	no
Treatment	yes	no	no	no	no	no	no

Table 4.81 Summary of Post-test Performance on Thinking Skills Measured by the CTSR for 14-year-old Males

Subject	Post-Treatment Thinking Skill Mastery						
	Conser-vation Mass	Conser-vation Volume	Propor-tional reasoning	Control of variable	Correla-tional reasoning	Proba-bility reasoning	Hypothetico-deductive reasoning
Control	yes	yes	no	no	no	no	no
Treatment	yes	no	no	yes	no	no	no

Table 4.82 Summary of in Subject's Thinking Skill Mastery as Measured by the CTSR for 14-year-old Males

Subject	Change in Thinking Skill Mastery
Control	–
Treatment	+ Control of variables

The control student did not have a change in thinking skill mastery. The treatment student gained mastery in the ability to identify and control variables, one of the formal thinking skills that were taught in the treatment.

Table 4.83 summarizes all of the data for the 14-year-old male subjects. Including their change in formal thinking skill ability, intelligence score, and mastery of specific formal thinking skills from pre-test to post-test.

Table 4.83 Summary of Pre-Treatment to Post-Treatment changes for CTSR, RPM, and Specific Thinking Skills for 14-year-old Males

Subject	CTSR (13)		RPM (60)		Thinking Skill Change
	Pre-Test	Post-Test	Pre-Test	Post-Test	
Control	2	3	48	50	–
Treatment	2	3	44	49	+ CV[a]

[a]CV: Control of variables

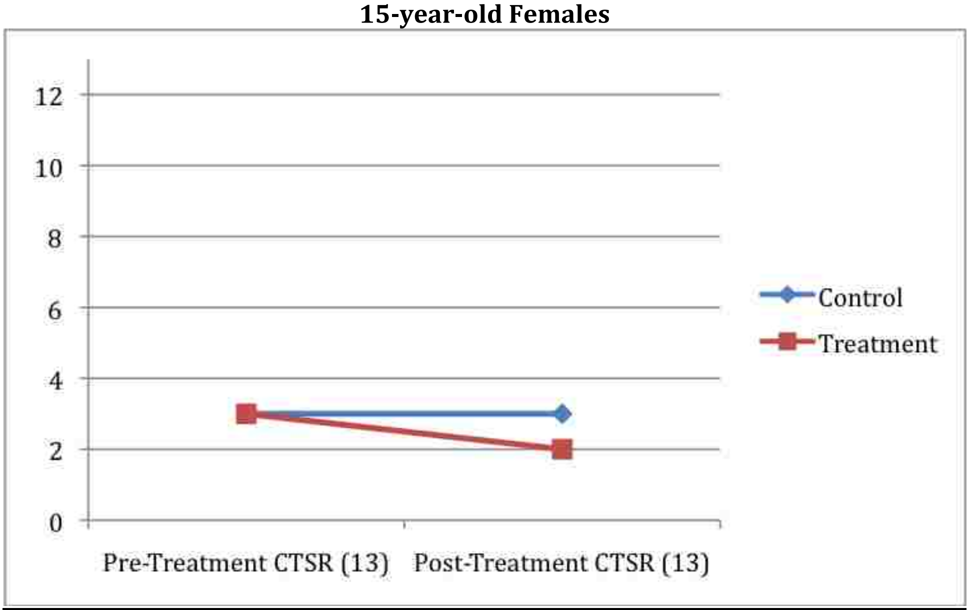
15-year-old Females

Table 4.84 and Figure 4.21 document potential changes in thinking skills during the study.

Table 4.84 Summary of Pre-treatment/Post-treatment Comparison of CTSR Statistics for 15-year-old Females

Subject	Pre-Treatment CTSR (13)	Post-Treatment CTSR (13)	Change	Thinking Skill Classification
Control	3	3	–	concrete
Treatment	3	2	–1	concrete

Figure 4.21. Summary of Pre-treatment/Post-treatment Comparison of CTSR Statistics for 15-year-old Females



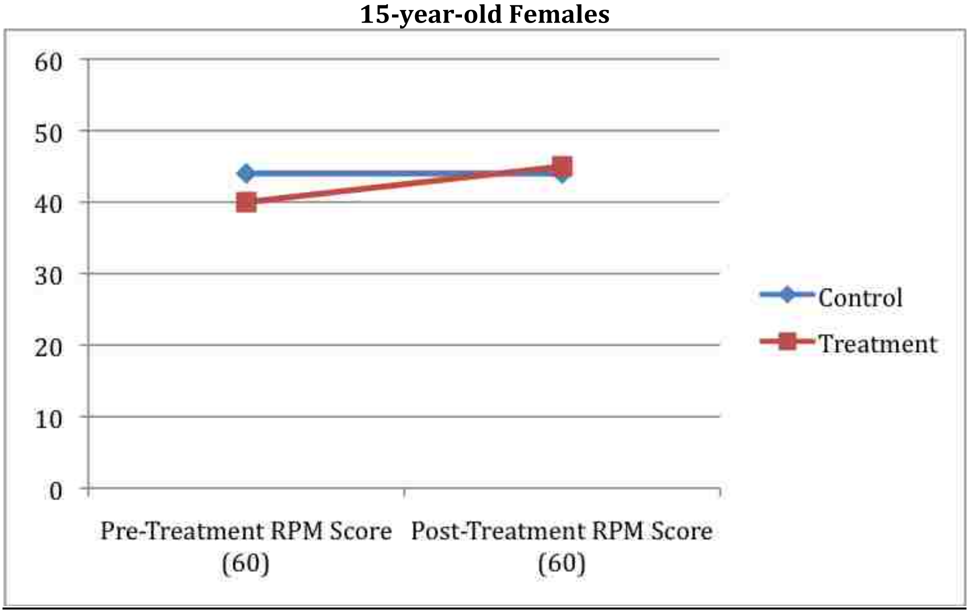
The control student did not have a change in thinking skill ability. The treatment student had a small decrease in thinking skill ability.

Table 4.85 and Figure 4.22 document potential changes in intelligence during the study.

Table 4.85 Summary of Pre-treatment/Post-treatment Comparison of RPM Statistics for 15-year-old Females

Subject	Pre-Treatment RPM Score (60)	Post-Treatment RPM Score (60)	Change
Control	44	44	–
Treatment	40	45	+5

Figure 4.22. Summary of Pre-treatment/Post-treatment Comparison of RPM Statistics for 15-year-old Females



The control student did not have a change in their intelligence score. The treatment student had a gain on their intelligence score.

Table 4.86 summarizes the potential changes in thinking skills and intelligence during the study.

Table 4.86 Summary of Pre- & Post-treatment change in CTSR & RPM Scores for 15-year-old Females

Subject	CTSR (13) Change	RPM Change
Control	–	–
Treatment	–1	+5

Tables 4.87-4.89 document potential changes in specific thinking skills during the study.

Table 4.87 Summary of Pre-test Performance on Thinking Skills Measured by the CTSR for 15-year-old Females

Subject	Pre-Treatment Thinking Skill Mastery						
	Conser-vation Mass	Conser-vation Volume	Propor-tional reasoning	Control of variable	Correla-tional reasoning	Proba-bility reasoning	Hypothetico-deductive reasoning
Control	yes	yes	no	no	no	no	no
Treatment	yes	no	no	no	no	no	no

Table 4.88 Summary of Post-test Performance on Thinking Skills Measured by the CTSR for 15-year-old Females

Subject	Post-Treatment Thinking Skill Mastery						
	Conser-vation Mass	Conser-vation Volume	Propor-tional reasoning	Control of variable	Correla-tional reasoning	Proba-bility reasoning	Hypothetico-deductive reasoning
Control	yes	yes	no	no	no	no	no
Treatment	yes	no	no	no	no	no	no

Table 4.89 Summary of Change in Thinking Skill Mastery as Measured by the CTSR for 15-year-old Females

Subject	Change in Thinking Skill Mastery
Control	–
Treatment	–

The control student and treatment student did not have a change in thinking skill mastery.

Table 4.90 summarizes all of the data for the 15-year-old female subjects. Including their change in formal thinking skill ability, intelligence score, and mastery of specific formal thinking skills from pre-test to post-test.

Table 4.90 Summary of Pre-Treatment to Post-Treatment changes for CTSR, RPM, and Specific Thinking Skills for 15-year-old Females

Subject	CTSR (13)		RPM (60)		Thinking Skill Change
	Pre-Test	Post-Test	Pre-Test	Post-Test	
Control	3	3	44	44	–
Treatment	3	2	40	45	–

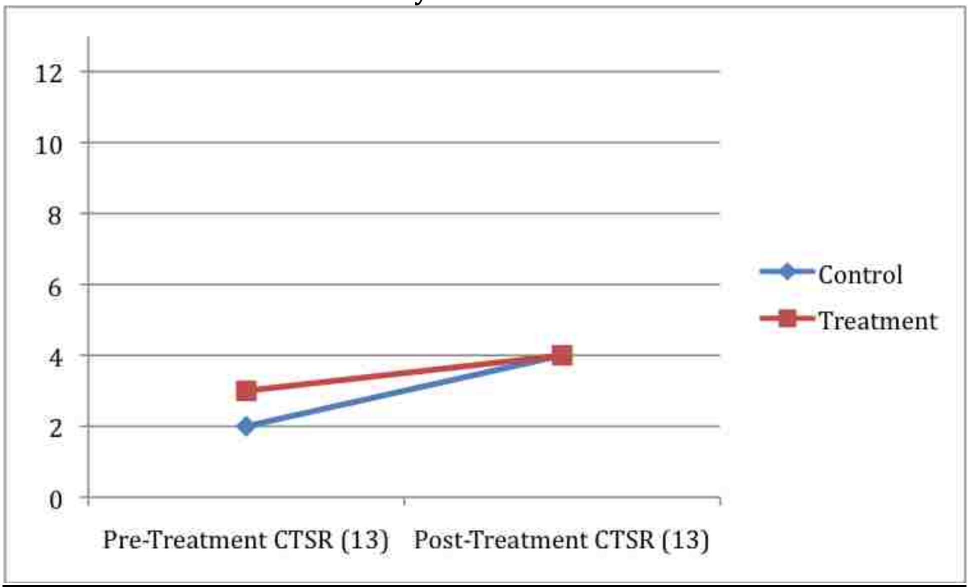
15-year-old Males

Table 4.91 and Figure 4.23 document potential changes in thinking skills during the study.

Table 4.91 Summary of Pre-treatment/Post-treatment Comparison of CTSR Statistics for 15-year-old Males

Subject	Pre-Treatment CTSR (13)	Post-Treatment CTSR (13)	Change	Thinking Skill Classification
Control	2	4	+2	early-transitional
Treatment	3	4	+1	early-transitional

Figure 4.23. Summary of Pre-treatment/Post-treatment Comparison of CTSR Statistics for 15-year-old Males



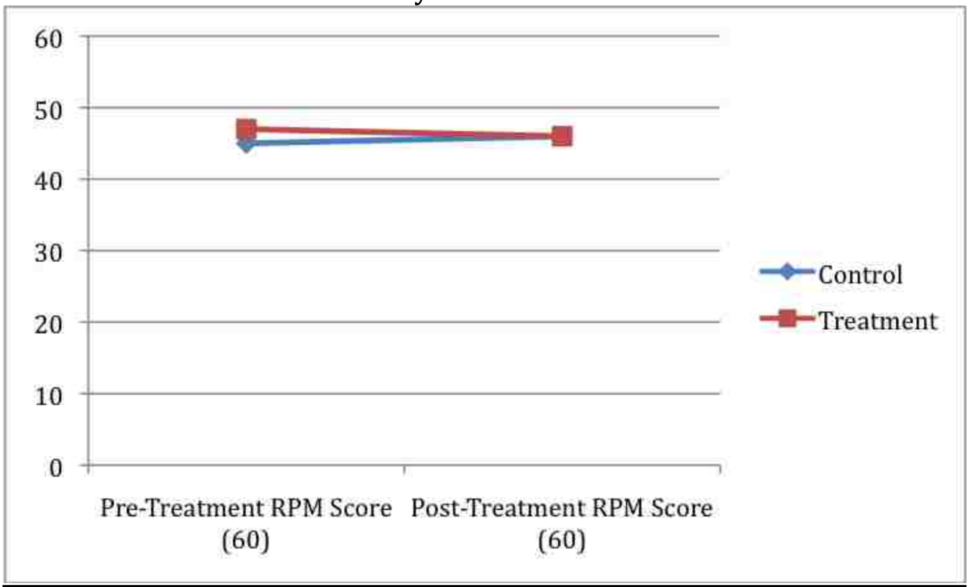
Both the control and treatment student had gains in thinking skill ability and moved from concrete thinkers to early-transitional thinkers. The control student had a larger gain in thinking skill ability.

Table 4.92 and Figure 4.24 document potential changes in intelligence during the study.

Table 4.92 Summary of Pre-treatment/Post-treatment Comparison of RPM Statistics for 15-year-old Males

Subject	Pre-Treatment RPM Score (60)	Post-Treatment RPM Score (60)	Change
Control	45	46	+1
Treatment	47	46	–1

Figure 4.24. Summary of Pre-treatment/Post-treatment Comparison of RPM Statistics for 15-year-old Males



The control student had a slight gain on their intelligence score. The treatment student had a slight decrease on their intelligence score.

Table 4.93 summarizes the potential changes in thinking skills and intelligence during the study.

Table 4.93 Summary of Pre- & Post-treatment change in CTSR & RPM Scores for 15-year-old Males

Subject	CTSR (13) Change	RPM (60) Change
Control	+2	+1
Treatment	+1	–1

Tables 4.94-4.96 document potential changes in specific thinking skills during the study.

Table 4.94 Summary of Pre-test Performance on Thinking Skills Measured by the CTSR for 15-year-old Males

Subject	Pre-Treatment Thinking Skill Mastery						
	Conser-vation Mass	Conser-vation Volume	Propor-tional reasoning	Control of variable	Correla-tional reasoning	Proba-bility reasoning	Hypothetico-deductive reasoning
Control	yes	no	no	no	no	no	no
Treatment	yes	no	no	no	no	no	no

Table 4.95 Summary of Post-test Performance on Thinking Skills Measured by the CTSR for 15-year-old Males

Subject	Post-Treatment Thinking Skill Mastery						
	Conser-vation Mass	Conser-vation Volume	Propor-tional reasoning	Control of variable	Correla-tional reasoning	Proba-bility reasoning	Hypothetico-deductive reasoning
Control	yes	no	no	no	no	no	no
Treatment	yes	no	no	yes	no	no	no

Table 4.96 Summary of Change in Thinking Skill Mastery as Measured by the CTSR for 15-year-old Males

Subject	Change in Thinking Skill Mastery
Control	–
Treatment	+ Control of variables

The control student did not have a change in thinking skill mastery. The treatment student gained mastery in the ability to identify and control variables, one of the formal thinking skills that were taught in the treatment.

Table 4.97 summarizes all of the data for the 15-year-old male subjects. Including their change in formal thinking skill ability, intelligence score, and mastery of specific formal thinking skills from pre-test to post-test.

Table 4.97 Summary of Pre-Treatment to Post-Treatment changes for CTSR, RPM, and Specific Thinking Skills for 15-year-old Males

Subject	CTSR (13)		RPM (60)		Thinking Skill Change
	Pre-Test	Post-Test	Pre-Test	Post-Test	
Control	2	4	45	46	–
Treatment	3	4	47	46	+ CV[a]

[a]CV: Control of variables

16-year-old Females

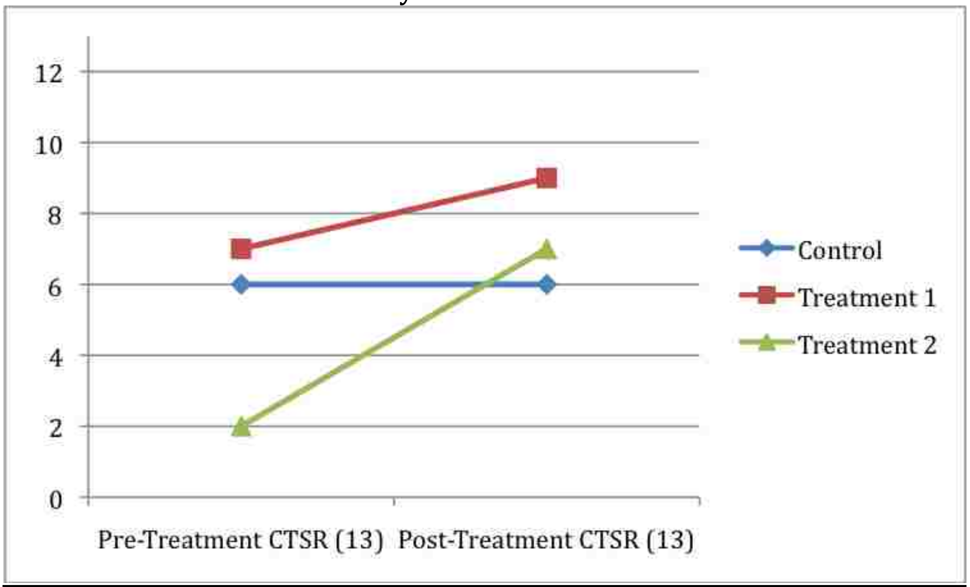
Table 4.98 and Figure 4.25 document potential changes in thinking skills during the study.

Table 4.98 Summary of Pre-treatment/Post-treatment Comparison of CTSR Statistics for 16-year-old Females

Subject	Pre-Treatment CTSR (13)	Post-Treatment CTSR (13)	Change	Thinking Skill Classification
Control[a]	6	6	–	early-transitional
Treatment 1[a]	7	9	+2	transitional
Treatment 2	2	7	+5	transitional

[a]These subjects did not begin as concrete operational thinkers

Figure 4.25. Summary of Pre-treatment/Post-treatment Comparison of CTSR Statistics for 16-year-old Females



The control student and the treatment 1 student both started the study as transitional thinkers. The control student did not have a change in thinking skill ability both treatment students had gains in thinking skill ability. The treatment 2 student moved from a concrete thinker to a transitional thinker.

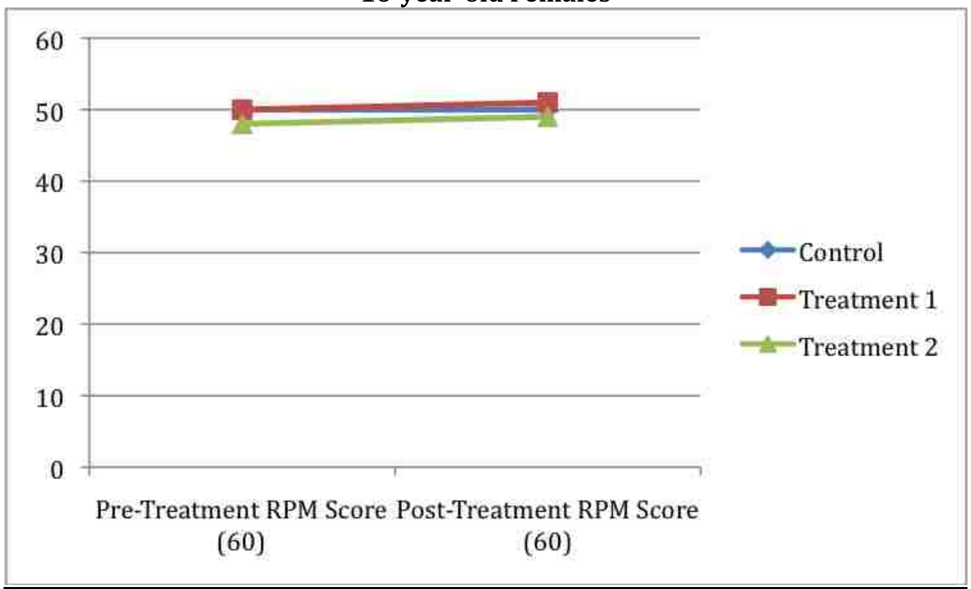
Table 4.99 and Figure 4.26 document potential changes in intelligence during the study.

Table 4.99 Summary of Pre-treatment/Post-treatment Comparison of RPM Statistics for 16-year-old Females

Subject	Pre-Treatment RPM Score (60)	Post-Treatment RPM Score (60)	Change
Control[a]	50	50	–
Treatment 1[a]	50	51	+1
Treatment 2	48	49	+1

[a]These subjects did not begin as concrete operational thinkers

Figure 4.26. Summary of Pre-treatment/Post-treatment Comparison of RPM Statistics for 16-year-old Females



The control student did not have a change in their intelligence score. Both treatment students had a small gain in their intelligence scores.

Table 4.100 summarizes the potential changes in thinking skills and intelligence during the study.

Table 4.100 Summary of Pre- & Post-treatment change in CTSR & RPM Scores for 16-year-old Females

Subject	CTSR (13) Change	RPM (60) Change
Control[a]	–	–
Treatment 1[a]	+2	+1
Treatment 2	+5	+1

[a]These subjects did not begin as concrete operational thinkers

Tables 4.101-4.103 document potential changes in specific thinking skills during the study.

Table 4.101 Summary of Pre-test Performance on Thinking Skills Measured by the CTSR for 16-year-old Females

Subject	Pre-Treatment Thinking Skill Mastery						
	Conser-vation Mass	Conser-vation Volume	Propor-tional reasoning	Control of variable	Correla-tional reasoning	Proba-bility reasoning	Hypothetic deductive reasoning
Control[a]	yes	yes	no	yes	no	no	no
Treatment 1[a]	yes	yes	no	yes	no	yes	no
Treatment 2	yes	no	no	no	no	no	no

[a]These subjects did not begin as concrete operational thinkers

Table 4.102 Summary of Post-test Performance on Thinking Skills Measured by the CTSR for 16-year-old Females

Subject	Post-Treatment Thinking Skill Mastery						
	Conser-vation Mass	Conser-vation Volume	Propor-tional reasoning	Control of variable	Correla-tional reasoning	Proba-bility reasoning	Hypothetic deductive reasoning
Control[a]	yes	yes	no	yes	no	no	no
Treatment 1[a]	yes	yes	yes	yes	yes	yes	no
Treatment 2	yes	no	no	yes	no	yes	no

[a]These subjects did not begin as concrete operational thinkers

Table 4.103 Summary of Change in Thinking Skill Mastery as Measured by the CTSR for 16-year-old Females

Subject	Change in Thinking Skill Mastery
Control[a]	–
Treatment 1[a]	+ Proportional reasoning, + Correlational reasoning
Treatment 2	+ Control of variables, + Probabilistic reasoning

[a]These subjects did not begin as concrete operational thinkers

The control student did not have a change in thinking skill mastery but did have mastery of the formal thinking ability of identifying and controlling variables and was identified as a transitional thinker before the study began. The treatment 1 student gained mastery in proportional reasoning, one of the formal thinking skills taught in the treatment as well as in correlational reasoning. The treatment 1 student had the formal thinking skills of probabilistic reasoning and the ability to identify and control variables before the study began. The treatment 1 student was also identified as a transitional thinker before the study began. The treatment 2 student gained mastery in proportional reasoning after the treatment, one of the formal thinking skills taught in the treatment and also gained the formal thinking skill of probabilistic reasoning after the treatment.

Table 4.104 summarizes all of the data for the 16-year-old female subjects. Including their change in formal thinking skill ability, intelligence score, and mastery of specific formal thinking skills from pre-test to post-test.

Table 4.104 Summary of Pre-Treatment to Post-Treatment changes for CTSR, RPM, and Specific Thinking Skills for 16-year-old Females

Subject	CTSR (13)		RPM (60)		Thinking Skill Change
	Pre-Test	Post-Test	Pre-Test	Post-Test	
Control[a]	6[a]	6[a]	50[a]	50[a]	–
Treatment 1[a]	7[a]	9[a]	50[a]	51[a]	+ Prop[c], + Corr[e]
Treatment 2	2	7	48	49	+ CV[d] + Prob[b]

[a]These subjects did not begin as concrete operational thinkers
[b]Prob: Probabilistic reasoning
[c]Prop: Proportional reasoning
[d]CV: Control of variables
[e]Corr: Correlational reasoning

16-year-old Males

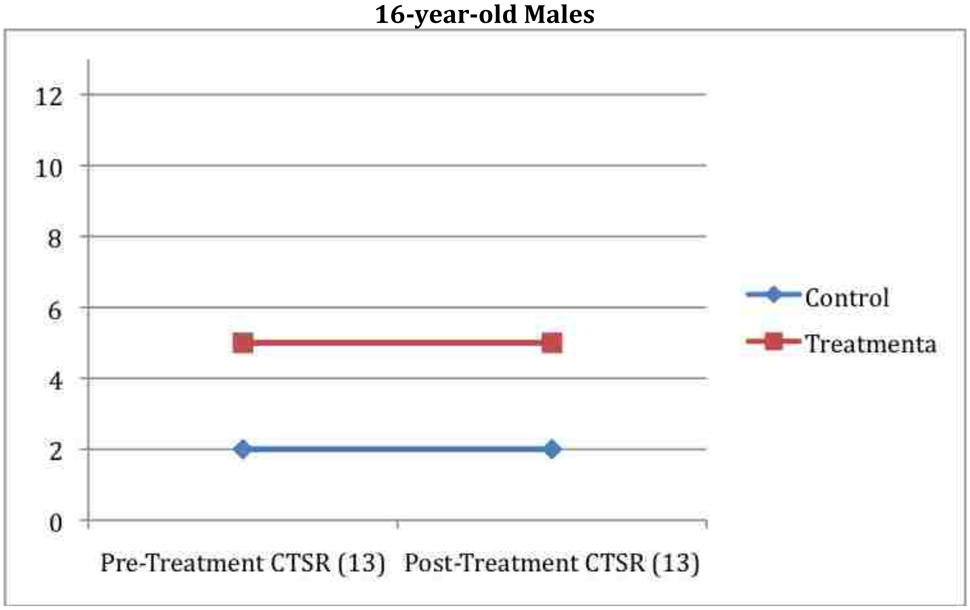
Table 4.105 and Figure 4.27 document potential changes in thinking skills during the study.

Table 4.105. Summary of Pre-treatment/Post-treatment Comparison of CTSR Statistics for 16-year-old Males

Subject	Pre-Treatment CTSR (13)	Post-Treatment CTSR (13)	Change	Thinking Skill Classification
Control	2	2	–	concrete
Treatment[a]	5	5	–	early-transitional

[a]This subject began the study as an early-transitional thinker

Figure 4.27. Summary of Pre-treatment/Post-treatment Comparison of CTSR Statistics for 16-year-old Males



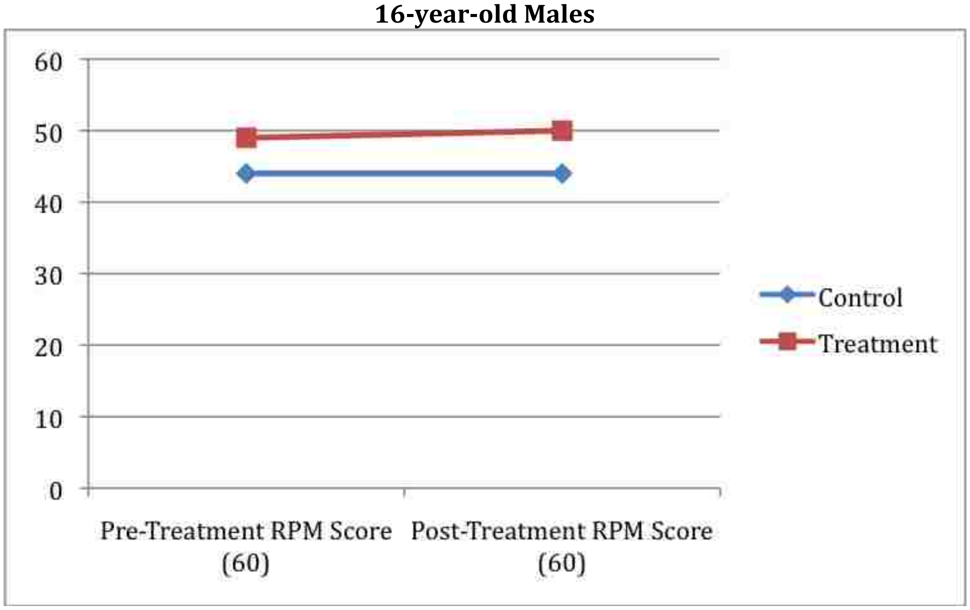
The control student and the treatment student did not have a change in thinking skill ability. The treatment student began the study as an early-transitional thinker.

Table 4.106 and Figure 4.28 document potential changes in intelligence during the study.

Table 4.106 Summary of Pre-treatment/Post-treatment Comparison of RPM Statistics for 16-year-old Males

Subject	Pre-Treatment RPM Score (60)	Post-Treatment RPM Score (60)	Change
Control	44	44	–
Treatment	49	50	+1

Figure 4.28. Summary of Pre-treatment/Post-treatment Comparison of RPM Statistics for 16-year-old Males



The control student had no change on their intelligence score. The treatment student had a slight gain on their intelligence score.

Table 4.107 summarizes the potential changes in thinking skills and intelligence during the study.

Table 4.107 Summary of Pre- & Post-treatment change in CTSR & RPM Scores for 16-year-old Males

Subject	CTSR (13) Change	RPM (60) Change
Control	–	–
Treatment[a]	–	+1

[a]This subject began the study as an early-transitional thinker

Tables 4.108-4.110 document potential changes in specific thinking skills during the study.

Table 4.108 Summary of Pre-test Performance on Thinking Skills Measured by the CTSR for 16-year-old Males

Subject	Pre-Treatment Thinking Skill Mastery						
	Conser-vation Mass	Conser-vation Volume	Propor-tional reasoning	Control of variable	Correla-tional reasoning	Proba-bility reasoning	Hypothetic deductive reasoning
Control	yes	yes	no	no	no	no	no
Treatment[a]	yes	yes	no	no	no	no	no

[a]This subject began the study as an early-transitional thinker

Table 4.109 Summary of Post-test Performance on Thinking Skills Measured by the CTSR for 16-year-old Males

Subject	Post-Treatment Thinking Skill Mastery						
	Conser-vation Mass	Conser-vation Volume	Propor-tional reasoning	Control of variable	Correla-tional reasoning	Proba-bility reasoning	Hypothetic deductive reasoning
Control	yes	yes	no	no	no	no	no
Treatment[a]	yes	yes	no	yes	no	yes	no

[a]This subject began the study as an early-transitional thinker

Table 4.110 Summary of Change in Thinking Skill Mastery as Measured by the CTSR for 16-year-old Males

Subject	Change in Thinking Skill Mastery
Control	–
Treatment[a]	+ Control of variables, + Probabilistic reasoning

[a]This subject began the study as an early-transitional thinker

The control student did not have a change in thinking skill mastery. The treatment student, who began the study as an early-transitional thinker, gained mastery in the ability to identify and control variables, one of the formal thinking skills that were taught in the treatment and in probabilistic reasoning after the treatment.

Table 4.111 summarizes all of the data for the 16-year-old male subjects. Including their change in formal thinking skill ability, intelligence score, and mastery of specific formal thinking skills from pre-test to post-test.

Table 4.111 Summary of Pre-Treatment to Post-Treatment changes for CTSR, RPM, and Specific Thinking Skills for 16-year-old Males

Subject	CTSR (13)		RPM (60)		Thinking Skill Change
	Pre-Test	Post-Test	Pre-Test	Post-Test	
Control	2	2	44	44	–
Treatment 1[a]	5[a]	5[a]	49[a]	50[a]	+ CV[c], + Prob[b]

[a]This subject began the study as an early-transitional thinker
[b]Prob: Probabilistic reasoning
[c]CV: Control of variables

Control and Treatment Group Comparison

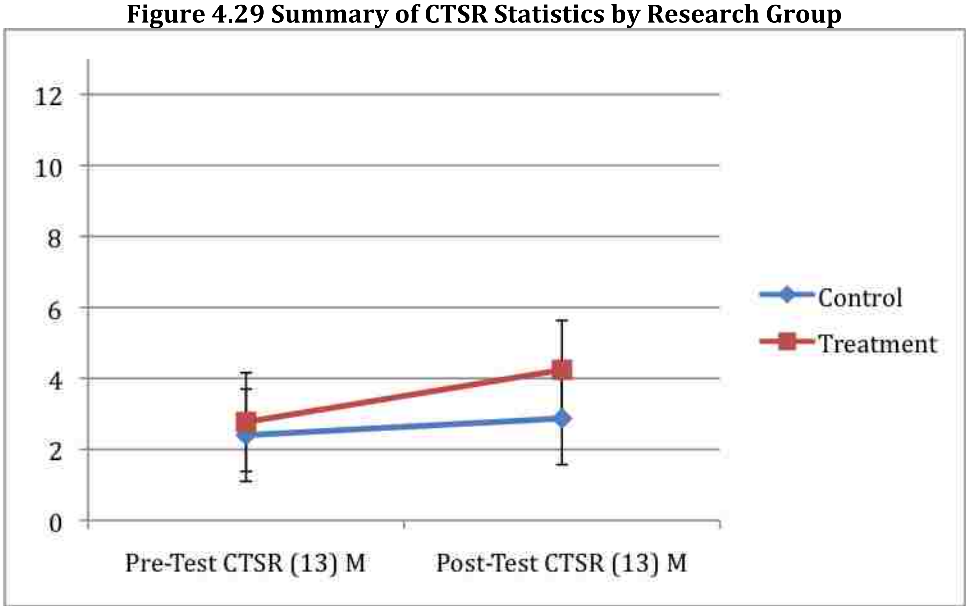
Table 4.112 and Figure 4.29 compare the thinking skill ability of the control group to the treatment group.

Table 4.112 Summary of CTSR Statistics by Research Group

Group	*n*	Pre-Test CTSR (13) *M*[a]	SD	Post-Test CTSR (13) *M*[a]	SD	Change
Control[b]	15	2.40	1.30	2.87	1.30	+0.47
Treatment[c]	17	2.77	1.39	4.24	1.99	+1.47

[a]Mean CTSR score
[b]One subject began as a transitional thinker
[c]One subject began as a transitional thinker and one subject began as an early transitional thinker

Figure 4.29 Summary of CTSR Statistics by Research Group



The treatment students as a whole had a larger gain in thinking skill ability than the control students.

Tables 4.113 and 4.114 summarize the results from the Mann-Whitney U-test, the non-parametric statistical equivalent of the independent samples *t*-test, for interval scale data. The U-test was used to compare the ordinal skill levels between the control and treatment subjects. This test compares the distributions of scores instead of the differences in average scores between groups. The U-test rank orders the data and determines the number of times a score from one group precedes a score from the second group. The test is used to determine if there is a statistical difference between two independent groups. Table 4.113 compares the control and treatment groups CTSR pre-test scores to ensure that the two groups began the study with equivalent formal thinking abilities so their post-test scores can be compared. Table 4.114 compares the post-test scores to determine if there is a significant difference between the two groups after the treatment.

Table 4.113 Mann-Whitney Independent Samples Test for Pre-Test CTSR Statistics By Research Group

Research Group	*n*	Mean Rank	*U*	*p*-value
		Pre-test CTSR (13)		
Control[a]	15	15.3	110	0.2611
Treatment[b]	17	17.5		

[a]One subject began as a transitional thinker
[b]One subject began as a transitional thinker and one subject began as an early transitional thinker

There are no significant differences between the distributions of control and treatment research groups for the pre-test CTSR at the 0.05 level of significance. This means the two groups began the study with equivalent formal thinking abilities and their post-test scores can be compared.

Table 4.114 Mann-Whitney Independent Samples Test for Post-Test CTSR Statistics By Research Group

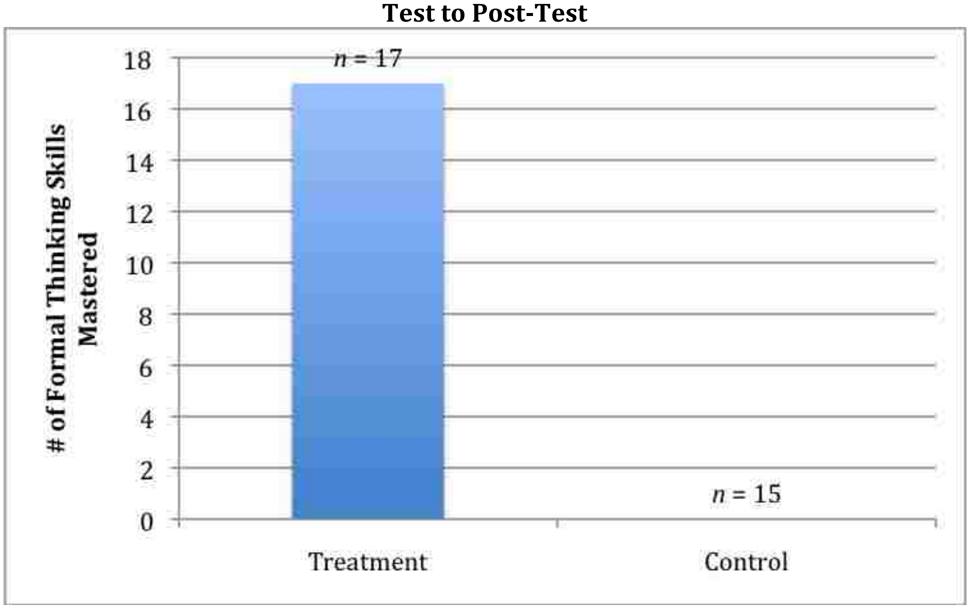
Research Group	*n*	Mean Rank	*U*	*p*-value
	Post-test CTSR (13)			
Control[a]	15	13.2	77.5	0.0307
Treatment[b]	17	19.4		

[a]One subject began as a transitional thinker
[b]One subject began as a transitional thinker and one subject began as an early transitional thinker

A significant difference in favor of the treatment students was found for change in thinking skill ability.

Figure 4.30 compares the number of formal thinking skills mastered from the pre-test to the post-test CTSR between the control group and the treatment group.

Figure 4.30 Summary of the Number of Formal Thinking Skills mastered from CTSR Pre-Test to Post-Test



The control group (n = 15) did not master any formal thinking skills after taking the pre-test CTSR, as measured by the post-test CTSR. Three of the control students had previously mastered the formal thinking skill of identifying and controlling variables. One of the control students had previously mastered the formal thinking skill of probabilistic reasoning. The treatment group (n =17) mastered seventeen formal thinking skills after completing the formal thinking skill intervention. Nine students gained the ability to identify and control variables; four students gained the ability of proportional reasoning; three students gained the ability of probabilistic reasoning; one student gained the ability of correlational reasoning. Before the treatment began two of the treatment subjects had previously mastered the ability to identify and control variables and one of the treatment subjects had mastered the ability of probabilistic reasoning.

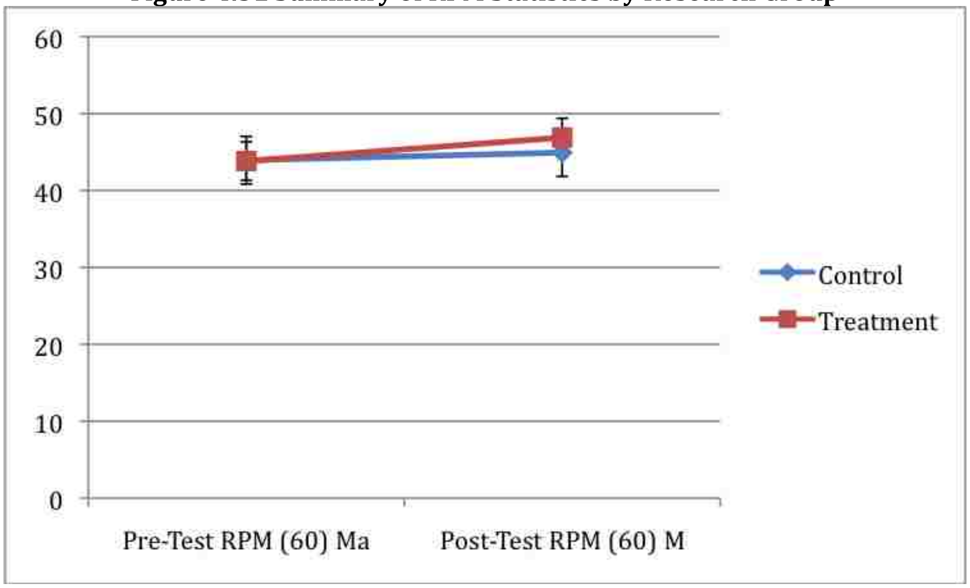
Table 4.115 and Figure 4.31 summarize the comparison of the control group and the treatment group on intelligence scores as measured by the RPM.

Table 4.115 Summary of RPM Statistics by Research Group

Group	*n*	Pre-Test RPM (60) *M*[a]	SD	Post-Test RPM (60) *M*	SD	Change
Control[b]	15	43.93	3.45	44.93	3.08	+1.00
Treatment[c]	17	43.82	4.16	46.88	2.50	+3.06

[a]Mean RPM score
[b]One subject began as a transitional thinker
[c]One subject began as a transitional thinker and one subject began as an early transitional thinker

Figure 4.31 Summary of RPM Statistics by Research Group



The treatment students as a whole had a larger gain in intelligence score than the control students.

Table 4.116 contains the non-parametric U-test results of the comparison between the two research groups.

Table 4.116 Mann-Whitney Independent Samples Test for Pre-Test and Post-Test RPM Statistics By Research Group

Research Group	*n*	Mean Rank	*U*	*p*-value
		Pre-test RPM		
Control[a]	15	16.3	124.5	0.4641
Treatment[b]	17	16.7		
		Post-test RPM		
Control[a]	15	13.1	76	0.0268
Treatment[b]	17	19.5		

[a]One subject began as a transitional thinker
[b]One subject began as a transitional thinker and one subject began as an early transitional thinker

There was not a significant difference between the two research groups on the pre-test RPM. This validates the post-test RPM comparison. A significant difference in favor of the treatment students was found for change in intelligence score.

Adolescent and Non-Adolescent Comparison for Treatment Subjects

The distinction of adolescence and non-adolescents by age was established by the following research studies (Hudspeth & Pribram, 1990; Shayer & Adey, 1993; Sowell et al., 1999; Stauder et al., 1993; Thatcher et al., 1987).

Female Adolescents Compared to Female Non-Adolescents Who Participated in the Thinking Skill Intervention

Table 4.117 and Figures 4.32 and 4.33 compare the change in thinking skill ability after the treatment for non-adolescent females, females aged 10-years-old and 14-16-years-old, to adolescent females, females aged 11-13-years old.

Table 4.117 Summary of CTSR Statistics For Females Who Underwent the Intervention

Group	*n*	Pre-Test CTSR (13) *M*[a]	SD	Post-Test CTSR (13) *M*[a]	SD	Change
Non-adolescents[b]	5	3.2	2.17	5.4	2.70	+2.2
Adolescents[c]	5	2.6	0.55	4.0	1.58	+1.4

[a]Mean CTSR score
[b]Ages 10 & 14-16. One student began the study as a transitional thinker
[c]Ages 11-13

Figure 4.32 Summary of CTSR Statistics For Females Who Underwent the Intervention

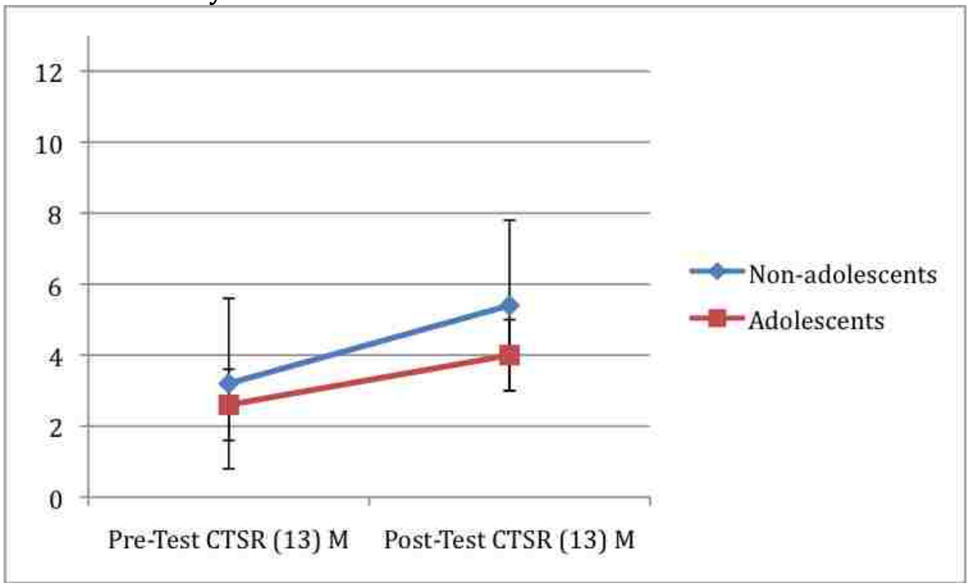
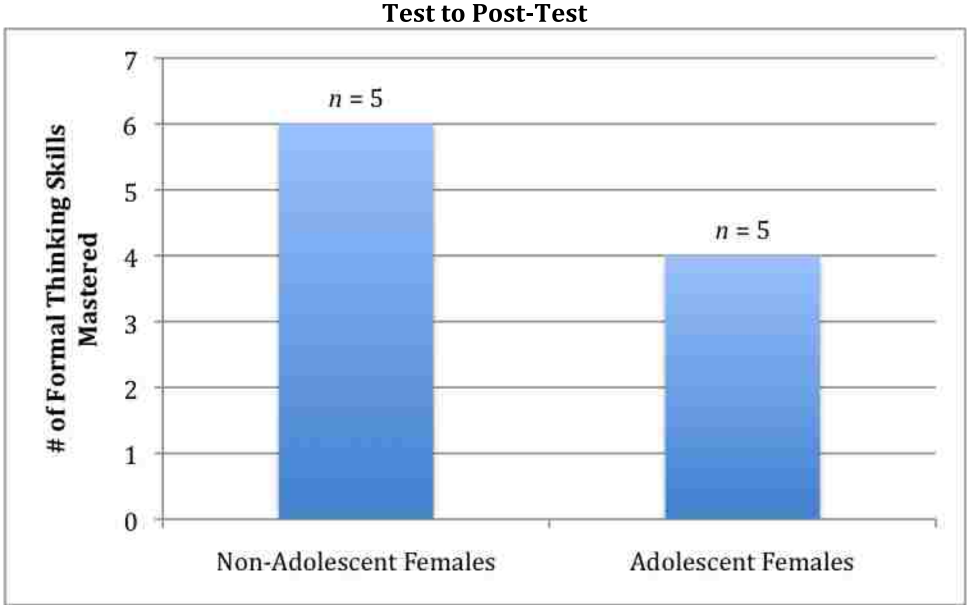


Figure 4.33 Summary of the Number of Formal Thinking Skills mastered from CTSR Pre-Test to Post-Test



There does not appear to be a difference in change in thinking skill ability between adolescent females and non-adolescent females in this study. It appears that non-adolescent females are able to learn formal thinking skills as well as adolescent females.

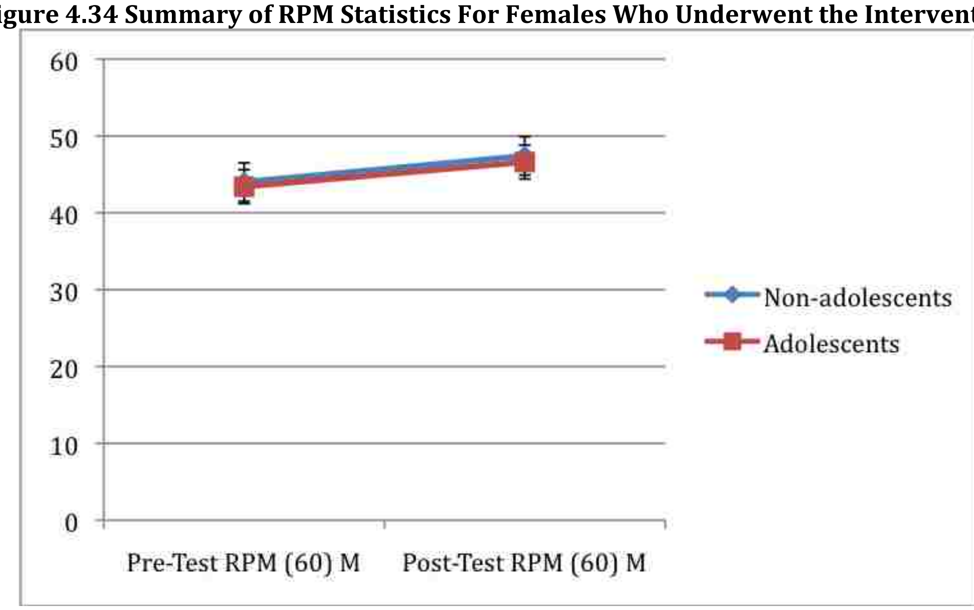
Table 4.118 and Figure 4.34 compare the change in intelligence after the treatment for non-adolescent females, females aged 10-years-old and 14-16-years-old, to adolescent females, females aged 11-13-years old.

Table 4.118 Summary of RPM Statistics For Females Who Underwent the Intervention

Group	*n*	Pre-Test RPM (60) *M*[a]	SD	Post-Test RPM (60) *M*[a]	SD	Change
Non-adolescents[b]	5	43.4	6.91	46.8	3.03	+3.4
Adolescents[c]	5	43.4	1.95	46.6	3.13	+3.2

[a]Mean RPM Score
[a]Ages 10 & 14-16. One student began the study as a transitional thinker
[b]Ages 11-13

Figure 4.34 Summary of RPM Statistics For Females Who Underwent the Intervention



There does not appear to be a difference in change intelligence between adolescent females and non-adolescent females in this study. It appears that non-adolescent females are able to improve their intelligence as well as adolescent females.

Male Adolescents Compared to Male Non-Adolescents Who Participated in the Thinking Skill Intervention

Table 4.119 and Figures 4.35 and 4.36 compare the change in thinking skill ability after the treatment for non-adolescent males, males aged 10-11-years-old and 15-16-years-old, to adolescent males, males aged 12-14-years old.

Table 4.119 Summary of CTSR Statistics For Males Who Underwent the Intervention

Group	*n*	Pre-Test CTSR (13) *M*[a]	SD	Post-Test CTSR (13) *M*[a]	SD	Change
Non-adolescents[b]	4	3.0	1.41	3.3	1.50	+0.3
Adolescents[c]	3	2.0	1.00	4.0	1.73	+2.0

[a]Mean CTSR score
[b]Ages 10-11 & 15-16. One student began the study as an early-transitional thinker
[c]Ages 12-14

Figure 4.35 Summary of CTSR Statistics For Males Who Underwent the Intervention

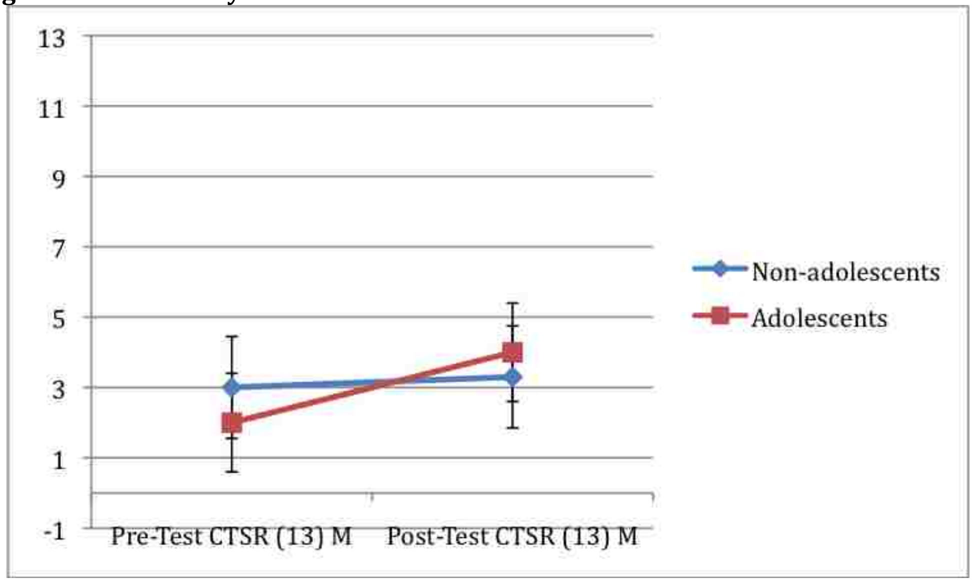
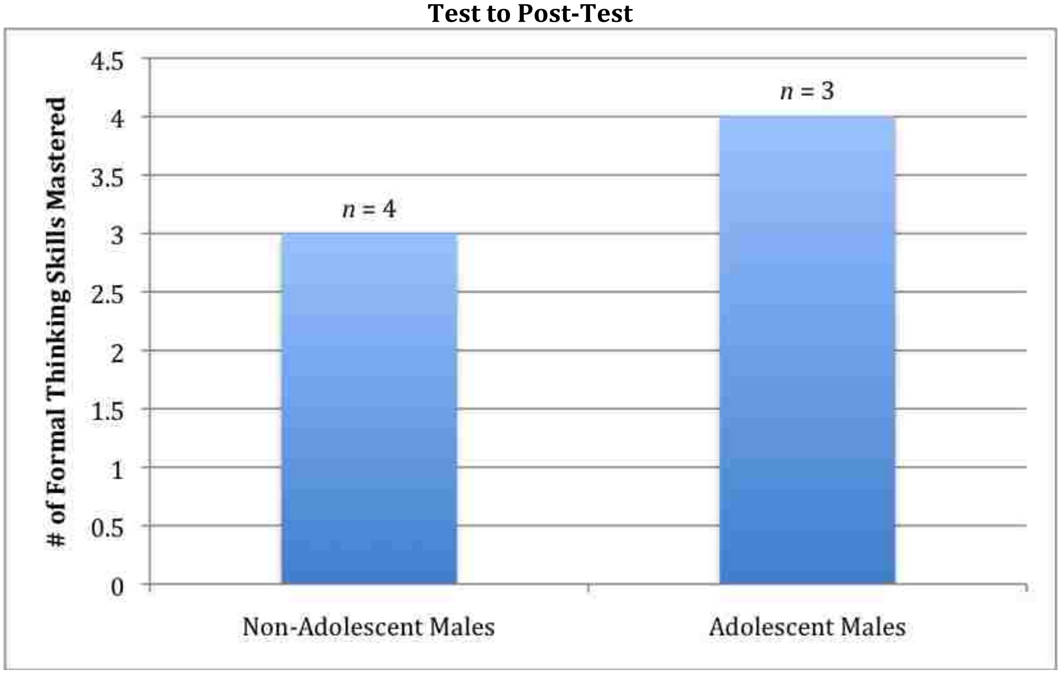


Figure 4.36 Summary of the Number of Formal Thinking Skills mastered from CTSR Pre-Test to Post-Test



The data from this study indicates that adolescent males may have an advantage in learning formal thinking skills over non-adolescent males when participating in a formal thinking skills training program.

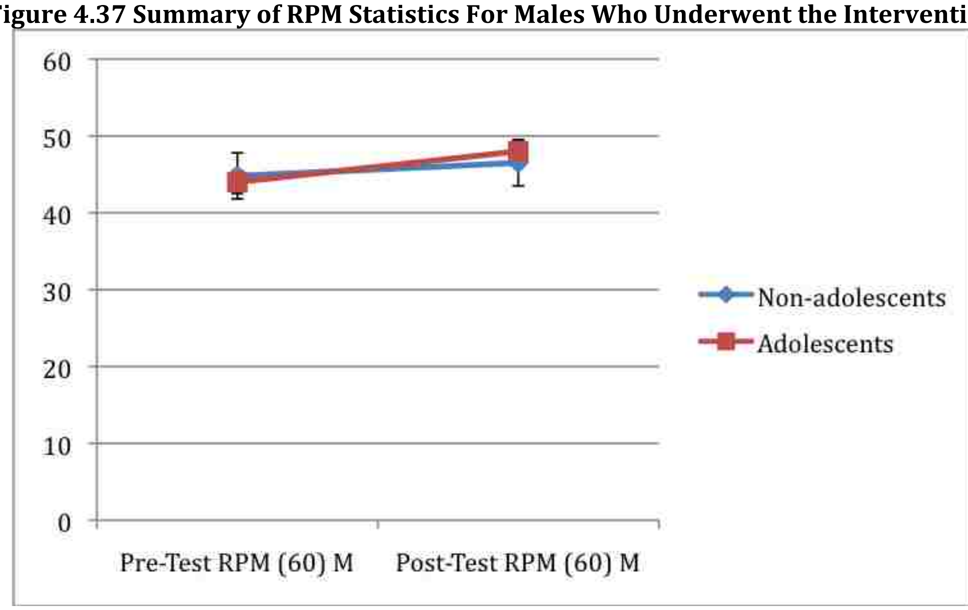
Table 4.120 and Figure 4.36 compare the change in intelligence after the treatment for non-adolescent males, males aged 10-11-years-old and 15-16-years-old, to adolescent males, males aged 12-14-years old.

Table 4.120 Summary of RPM Statistics For Males Who Underwent the Intervention

Group	*n*	Pre-Test RPM (60) *M*[a]	SD	Post-Test RPM (60) *M*[a]	SD	Change
Non-adolescents[b]	4	44.8	4.35	46.5	2.38	+1.7
Adolescents[c]	3	44.0	2.00	48.0	1.00	+4.0

[a]Mean RPM score
[b]Ages 10-11 & 15-16. One student began the study as an early-transitional thinker
[c]Ages 12-14

Figure 4.37 Summary of RPM Statistics For Males Who Underwent the Intervention



The data from this study indicates that adolescent males may have an advantage in improving their intelligence over non-adolescent males when participating in a formal thinking skills training program.

Research Questions

1. Will students who are taught to develop their formal thinking skills in eight science class replacement intervention sessions achieve significantly greater scores on measures of formal thinking skills than students of the same age who do not undergo the intervention?
    a. Will the scores on the control and exclusion of variables and proportionality reasoning skills targeted in the intervention sessions be greater for the treatment students when they are compared to the control students by age?
    b. Will the scores on the formal thinking skills not specifically targeted in the intervention sessions be greater for the treatment students when they are compared to the control students by age?

The determination of whether formal thinking skills can be taught using an intensive short-term formal thinking skill focused intervention was measured using the CTSR. Student's general formal thinking skill ability as well as their ability to master specific formal thinking skills was measured. Two formal thinking skills were taught for the intervention: the ability to identify and control variables and proportional reasoning. Other formal thinking skills were also measured by the CTSR to determine if the treatment had an effect on student formal thinking skill ability overall and if students mastered other formal thinking skills.

General Formal Thinking Skill Ability

Due to the qualitative nature and small scale of the study it is important to take into account each subject when determining the effectiveness of the intervention at improving students formal thinking skill ability in conjunction with comparing the treatment subjects to the control subjects. Tables 4.8, 4.10, 4.11, and 4.12 summarize the pre-treatment and post-treatment comparison of every subject's formal thinking skills. Fourteen of the seventeen treatment students had some improvement in their overall thinking skill ability after the treatment. Two of the treatment students did not have a change in their formal thinking skill score and one of the students had a decrease in their score. Ten of the seventeen treatment students moved from concrete thinkers to early-transitional thinkers after the treatment. One of the treatment students began the study as an early-transitional thinker and after the treatment moved to a transitional thinker. One of the treatment students moved from a concrete thinker to a transitional thinker. Four of the treatment students remained concrete thinkers after the treatment. One of the treatment students began the study as an early-transitional thinker and remained an early-transitional thinker after the treatment. Five of the fifteen control students had some improvement in their overall thinking skill score. Nine of the fifteen control students thinking skill ability score remained the same and one of the control students had a decrease in their thinking ability score. Two of the fifteen control students moved from concrete thinkers to early-transitional thinkers after taking the CTSR post-test. Twelve of the control students remained concrete thinkers. One of the control students began the study as a transitional thinker and did not change after the taking the post-test. Table 4.12 summarizes students' change in formal thinking skill mastery. None of the control students gained or lost a specific formal thinking skill (e.g., proportional reasoning). Eleven of the seventeen treatment students gained seventeen specific formal thinking skills. Five of the students gained one skill and six of the students gained two skills. None of the treatment students lost a specific formal thinking skill.

Table 4.112 directly compares the change in thinking skill ability of the control group to the treatment group. There is not a significant difference between the pre-test distributions of the two research groups (Table 4.113) which allows for a direct comparison of the post-test scores of the two groups. There is a significant difference between the post-test scores between the control group and the treatment group (Table 4.114). The data indicates that the treatment did improve the thinking skill ability of the control group as well as leading to a higher level of thinking skills. The treatment group as a whole moved from a classification of concrete thinkers to early-transitional thinkers.

<u>Formal Thinking Skills Taught in the Intervention</u>

Control of Variables – The ability to identify and control variables was one of the two formal thinking skills focused upon in the treatment intervention. Table 4.12 delineates the any changes subjects had in mastering a formal thinking skill they had not mastered previous to the treatment. As described above none of the control students gained or lost a specific formal thinking skill. As Tables 4.2 and 4.6 indicate three of the control students began and ended the study with the control of variables thinking skill ability and two of the treatment subjects began the study with the ability to identify and control variables in an experiment. Table 4.12 shows that nine of the seventeen treatment students gained the ability of controlling variables after the treatment and six of the treatment students did not gain the ability.

Proportional Reasoning – Proportional reasoning was the other formal thinking skill that was taught during the treatment intervention. Table 4.2 shows none of the control subjects or treatment subjects had mastered the formal thinking skill of proportional reasoning. As seen in Table 4.12 four of the treatment students gained the ability to reason proportionally after the treatment.

Formal Thinking Skills Not Taught in the Intervention

Correlational Reasoning – As Table 4.2 shows none of the subjects began the study with the ability to perform correlational reasoning. One treatment student, subject CC-16-F-T (Table 4.6 & Table 4.12) gained the ability of correlational reasoning after the treatment. No other students, control or treatment, gained the correlational reasoning thinking skill.

Probabilistic Reasoning – As Table 4.2 indicates one control student and one treatment student began the study with the ability to perform probabilistic reasoning. Table 4.6 and Table 4.12 show that three of the treatment students gained the probabilistic reasoning thinking skill after the treatment. None of the control students gained the probabilistic reasoning thinking skill.

Hyptothetico-deductive Reasoning – None of the treatment or control subjects began or finished the study with the formal thinking skill of hypothetico-deductive reasoning (Tables 4.2, 4.6, & 4.12).

2. Will some age levels have more success learning formal thinking skills than other age groups?
    a. Will adolescent boys aged 12-14 achieve greater scores on measures of formal thinking skills than pre-adolescent boys aged 10-11 and post-adolescent boys aged 15-16?
    b. Will adolescent girls aged 11-13 achieve greater scores on measures of formal thinking skills than pre-adolescent girls at an age of 10 and post-adolescent girls aged 14-16?

Shayer and Adey's (1993) CASE study provided evidence that adolescence may be a critical period for learning formal thinking skills. This question has not been investigated further. The Shayer and Adey study determined that the ages where the thinking skill training was the most effective was ages 11-13 for girls and 12-14 for boys, ages that match the general adolescence period for each sex. The determination of whether formal thinking skills are learned more readily during adolescence was measured using the CTSR. Student's general formal thinking skill ability as well as their ability to master specific formal thinking skills was measured. To answer this research question the data of the males and females were grouped into two groups each and compared. The males' were grouped by the ages of 12-14 (adolescence) and compared to the males aged 10-11 and 15-16 (non-adolescence). The females were grouped by the ages 11-13 (adolescence) and compared to the females aged 10 and 14-16 (non-adolescence).

Male Adolescence (ages 12-14) and Male Non-adolescence (ages 10-11, 15-16) Comparison

Table 4.119 and Figures 4.35 and 4.36 show the comparison between the adolescent males and the non-adolescent males thinking skills pre- and post-treatment. The data does show a difference between the two groups. The non-adolescent group has a slight increase in their thinking skill score while the adolescent group has a much larger increase. The non-adolescent males started at a higher level of formal thinking skill but after the treatment the adolescent males finished with the higher formal thinking skill score. The non-adolescent group (n = 4) gained mastery of three formal thinking skills after the intervention whereas the adolescent group (n = 3) gained mastery of four skills. The 16-year-old subject began the study as an early-transitional thinker and gained mastery of two (out of the three) of the formal thinking skills for the non-adolescent group.

Adolescent boys aged 12-14 appear to have an advantage in improving their scores on measures of formal thinking skills than pre-adolescent boys at an age of 10-11 and post adolescent boys aged 15-16.

Female Adolescence (ages 11-13) and Female Non-adolescence (ages 10, 14-16) Comparison

Table 4.117 and Figures 4.32 and 4.33 show the comparison between the adolescent females and the non-adolescent females thinking skills pre- and post-treatment. The data does not show a significant difference between the two groups. Both groups had increases in formal thinking skills scores. The non-adolescent females started at a higher level of formal thinking skill (M = 8.6) and had a slightly larger increase in formal thinking skills (+4.0) from pre-test to post-test than the adolescents (M = 6.6, +3.4). The non-adolescent group gained mastery of six formal thinking skills after the intervention whereas the adolescent group gained mastery of four skills. One of the two 16-year-old subjects began the study as a transitional thinker. Each group consists of five students. The 10-year-old subject did not gain a mastery of any new thinking skills but they did have an increase in their formal thinking skill score.

Adolescent girls aged 11-13 do not appear to have an advantage or a disadvantage in improving their scores on measures of formal thinking skills than pre-adolescent girls at an age of 10 and post-adolescent girls aged 14-16. It appears both groups of students can improve their formal thinking skills.

Comparison Of Treatment Subjects by Age and Gender

Tables 4.14-4.111 and Figures 4.1-4.28 summarize the data for the treatment subjects by age and gender. Generalizations of the data are dangerous when looking at individual students but in accord with the case study nature of this study the data of the individual students will be analyzed as general trends can be found, especially in regard to an adolescent effect in learning formal thinking skills.

The pre-adolescent males and females (Tables 4.14-4.4.27, 4.35-4.41 and Figures 4.1-4.4, 4.7-4.8) had almost no gains in formal thinking skills; the 10-year-old female had only a slight gain in thinking skills. None of the pre-adolescent students (*n* = 7) had mastery of any formal thinking skills before the treatment and none of the pre-adolescent student gained mastery of any formal thinking skills after the treatment.

Both the adolescent males and females had relatively large gains in formal thinking skills (Tables 4.28-4.34, 4.42-4.69, 4.77-4.83 and Figures 4.5-4.6, 4.9-4.16, 4.19-4.20). Looking at each treatment adolescent student individually, every student had very large gains in their formal thinking skill scores (minimum increase of +4 on their CTSR (24) score) except the 12-year-old female (+1 on her CTSR (24) score). Together the treatment adolescent males and females (*n* = 8) gained mastery of eight formal thinking skills after the treatment. Before the treatment one of the 13-year-old female students had previously mastered the control of variables thinking skill.

The post-adolescent treatment males and females had mixed results on their formal thinking skills (Tables 4.70-4.76, 4.84-4.111 and Figures 4.17-4.18, 4.21-4.28). The 14-year-old female, both 16-year-old females and the 15-year-old male all had large gains in their formal thinking skill scores. The 15-year-old female treatment student had a slight decrease in her formal thinking skill score and the 16-year-old male had no change in his score. Every post-adolescent student gained mastery of at least one formal thinking skill after the treatment, except the 15-year-old female student. Together the post-adolescent treatment students (n = 6) gained mastery of nine formal thinking skills after the treatment. Before the treatment one of the 16-year-old female students had previously mastered the control of variables thinking skill and the probabilistic reasoning skill.

The pre-adolescent treatment students were unable to improve their scores on measures of formal thinking skills or gain mastery of any specific formal thinking skills. The adolescent treatment student were able to achieve large improvements on their scores on measures of formal thinking skills as well as gain mastery of specific formal thinking skills. The post-adolescent treatment students were also able to achieve large improvements on their scores on measures of formal thinking skills as well as gain mastery of specific formal thinking skills.

3. Will students who are taught to develop their formal thinking skills in eight science class replacement intervention sessions achieve greater scores on measures of intelligence than students of the same age who do not undergo the training?

Can inquiry-based instruction improve students' intelligence? Many believe that intelligence is determined primarily by genetics; can a research based instructional method improve students intelligence relative to the traditional method of science instruction? The determination of whether an intensive short-term formal thinking skill focused intervention program can improve students' intelligence was measured using the RPM.

Intelligence

Tables 4.9 and 4.10 summarize the pre-treatment and post-treatment comparison of the every subject's intelligence. Fourteen of the seventeen treatment students had some improvement in their intelligence score after the treatment. Two of the treatment students had a slight decrease in their intelligence score and one of the treatment students did not have a change in their score. Eight of the fifteen control students had some improvement in their overall intelligence score. Four of the fifteen control students' intelligence score remained the same and three of the control students had a decrease in their intelligence score.

Tables 4.115 and Figure 4.31 directly compare the change in intelligence of the control group to the treatment group. There is not a significant difference between the pre-test distributions of the two research groups which allows for a direct comparison of the post-test scores of the two groups. There is a significant difference between the post-test scores between the control group and the treatment group. The data indicates that the treatment did improve the intelligence of the treatment group.

CHAPTER V

DISCUSSION AND CONCLUSIONS

This chapter presents a summary of the results of the measures and discusses the findings in the context of the four research questions. The chapter ends with a description of the general conclusions from the results of the study, and suggestions for future research.

Discussion

The discussion is organized around the four research questions that guided the evaluation of the effectiveness of the thinking skill intervention program. The results of the study are summarized again for each measure and then discussed in terms of the research questions.

Research Question One

1. Will students who are taught to develop their formal thinking skills in eight science class replacement intervention sessions achieve significantly greater scores on measures of formal thinking skills than students of the same age who do not undergo the intervention?
    a. Will the scores on the control and exclusion of variables and proportionality reasoning skills targeted in the intervention sessions be greater for the treatment students when they are compared to the control students by age?

b. Will the scores on the formal thinking skills not specifically targeted in the intervention sessions be greater for the treatment students when they are compared to the control students by age?

The determination of whether formal thinking skills can be taught using an intensive short-term formal thinking skill focused intervention was measured using the CTSR. Student's general formal thinking skill ability as well as their ability to master specific formal thinking skills was measured. Two formal thinking skills were taught for the intervention: the ability to identify and control variables and proportional reasoning. Other formal thinking skills were also measured by the CTSR to determine if the treatment had an effect on student formal thinking skill ability overall and if students mastered other formal thinking skills.

General Formal Thinking Skill Ability

Due to the qualitative nature and small scale of the study it is important to take into account each subject when determining the effectiveness of the intervention at improving students formal thinking skill ability in conjunction with comparing the treatment subjects to the control subjects. Tables 4.8, 4.10, 4.11, and 4.12 summarize the pre-treatment and post-treatment comparison of every subject's formal thinking skills. Fourteen of the seventeen treatment students had some improvement in their overall thinking skill ability after the treatment. Two of the treatment students did not have a change in their formal thinking skill score and one of the students had a decrease in their score. Ten of the seventeen treatment students moved from concrete thinkers to early-transitional thinkers after the treatment. One of the treatment students began the study as an early-transitional thinker and after the treatment moved to a transitional thinker. One of the treatment students moved from a concrete thinker to a transitional thinker. Four of the treatment students remained concrete thinkers after the treatment. One of the treatment students began the study as an early-transitional thinker and remained an early-transitional thinker after the treatment. Five of the fifteen control students had some improvement in their overall thinking skill score. Nine of the fifteen control students thinking skill ability score remained the same and one of the control students had a decrease in their thinking ability score. Two of the fifteen control students moved from concrete thinkers to early-transitional thinkers after taking the CTSR post-test. Twelve of the control students remained concrete thinkers. One of the control students began the study as a transitional thinker and did not change after the taking the post-test. Table 4.12 summarizes students' change in formal thinking skill mastery. None of the control students gained or lost a specific formal thinking skill (e.g., proportional reasoning). Eleven of the seventeen treatment students gained seventeen specific formal thinking skills. Five of the students gained one skill and six of the students gained two skills. None of the treatment students lost a specific formal thinking skill.

Table 4.112 directly compares the change in thinking skill ability of the control group to the treatment group. There is not a significant difference between the pre-test distributions of the two research groups (Table 4.113) which allows for a direct comparison of the post-test scores of the two groups. There is a significant difference between the post-test scores between the control group and the treatment group (Table 4.114). The data indicates that the treatment did improve the thinking skill ability of the control group as well as leading to a higher level of thinking skills. The treatment group as a whole moved from a classification of concrete thinkers to early-transitional thinkers.

Formal Thinking Skills Taught in the Intervention

Control of Variables – The ability to identify and control variables was one of the two formal thinking skills focused upon in the treatment intervention. Table 4.12 delineates the any changes subjects had in mastering a formal thinking skill they had not mastered previous to the treatment. As described above none of the control students gained or lost a specific formal thinking skill. As Tables 4.2 and 4.6 indicate three of the control students began and ended the study with the control of variables thinking skill ability and two of the treatment subjects began the study with the ability to identify and control variables in an experiment. Table 4.12 shows that nine of the seventeen treatment students gained the ability of controlling variables after the treatment and six of the treatment students did not gain the ability.

Proportional Reasoning – Proportional reasoning was the other formal thinking skill that was taught during the treatment intervention. Table 4.2 shows none of the control subjects or treatment subjects had mastered the formal thinking skill of proportional reasoning. As seen in Table 4.12 four of the treatment students gained the ability to reason proportionally after the treatment.

<u>*Formal Thinking Skills Not Taught in the Intervention*</u>

Correlational Reasoning – As Table 4.2 shows none of the subjects began the study with the ability to perform correlational reasoning. One treatment student, subject CC-16-F-T (Table 4.6 & Table 4.12) gained the ability of correlational reasoning after the treatment. No other students, control or treatment, gained the correlational reasoning thinking skill.

Probabilistic Reasoning – As Table 4.2 indicates one control student and one treatment student began the study with the ability to perform probabilistic reasoning. Table 4.6 and Table 4.12 show that three of the treatment students gained the probabilistic reasoning thinking skill after the treatment. None of the control students gained the probabilistic reasoning thinking skill.

Hyptothetico-deductive Reasoning – None of the treatment or control subjects began or finished the study with the formal thinking skill of hypothetico-deductive reasoning (Tables 4.2, 4.6, & 4.12).

Discussion

Due to the small scale of the study the data from this project can only demonstrate what is possible and cannot indicate that what is not possible. For example, because the ten-year-old male treatment student did not improve his formal thinking skills after the treatment does not indicate the inability of male students that age to obtain formal thinking skills. The data can support the hypothesis and strengthen it or it can cast doubt on the hypothesis. Part of the hypothesis, which comes from the theoretical framework of this study, discussed in Chapter II and from which the first research question was derived, asks whether an intensive intervention is an effective method of teaching students thinking skills relative to a standard high school or middle school science course is that formal thinking skills can be taught. The prevailing American opinion is that intelligence is immutable (Neisser et al., 1996), specifically individuals' ability to learn the skills necessary to succeed in science. Even Piaget, whose theory provides much of the backbone of the theoretical framework for this study, did not consider this question important because he believed that students' ability to develop formal thinking skills was mostly innate. Research over the last few decades indicates that the question is critical. If students do not develop formal thinking skills they are at a serious disadvantage in life, not just in the sciences but also in everyday life (Lawson, 1985). The importance of thinking skills is thoroughly addressed in the introduction and the literature review of this dissertation.

The data indicates that students who are taught to develop their formal thinking skills in eight science class replacement intervention sessions will achieve greater scores on measures of formal thinking skills than students of the same age who do not undergo the intervention.

The second part of the first research question seeks to determine whether the scores on the control and exclusion of variables and proportionality reasoning skills targeted in the intervention sessions will be greater for the treatment students when they are compared to the control students by age. As was described previously, none of the control students gained mastery of any formal thinking skills during the duration of the study. The data described above indicates that the intervention sessions successfully helped students develop the targeted formal thinking skills. Of the ten treatment students who obtained a mastery of a formal thinking skill after the treatment and did not have a previous understanding of the control variables thinking skill, nine of the students gained the control of variables skill. Four of the treatment students developed proportional reasoning after the intervention. None of the subjects in the study, treatment or control, had mastery of the proportional reasoning skill previous to the study. This may indicate the difficulty of this thinking skill and explain why fewer of the treatment students mastered the skill after the treatment. It was apparent during and after the intervention sessions that proportional reasoning was a more cognitively challenging skill than the control of variables skill, and the results of the study support this observation. Although not all of the treatment students gained the two formal thinking skills that were focused upon in the intervention sessions, those skills were mastered by some of the treatment students in a relatively short amount of time, and none of the control students mastered any formal thinking skills during the same time period. This evidence strongly indicates that the intervention was successful in improving the treatment students' ability on the control and exclusion of variables and proportionality reasoning skills targeted in the intervention sessions.

The third part of the first research question asks whether there is a formal thinking skills transfer effect: will the treatment students improve in the thinking skills that were not covered in the training? According to Piaget's theory, there is a high correlation between all of the formal thinking skills, therefore, students who are competent in one skill should be competent in the other skills (formal operational thinker). Consequently, this would indicate that if students developed some formal thinking skills as a result of a formal thinking skill intervention, there should be the potential of a transfer effect, that is, the students may concurrently develop other formal thinking skills as a result of the treatment despite not being directly taught those skills. As was reported (Table 4.13), eleven of the treatment students gained mastery of at least one formal thinking skill after the treatment. Thirteen of the seventeen skills that were gained were the two formal thinking skills that were focused upon in the interventions; therefore, four of the skills were gained without any explicit instruction during the intervention. The short time scale of the study coupled with the absence of any control subjects gaining mastery of any of the formal thinking skills suggests that there is a possibility of a formal thinking skill transfer effect.

The results of the study indicate that formal thinking skills can be developed if they are taught using an inquiry-based approach, which focuses specifically on the formal thinking skills. The study also lends support to Piaget's genetic epistemology theory that claims that there is a high correlation between all of the formal thinking skills. Students developed formal thinking skills that were not taught to them. This provides support to the veracity of Piaget's theory regarding the concrete operational to formal operational stage transition.

Research Question Two

2. Will some age levels have more success learning formal thinking skills than other age groups?
    a. Will adolescent boys aged 12-14 achieve greater scores on measures of formal thinking skills than pre-adolescent boys aged 10-11 and post-adolescent boys aged 15-16?
    b. Will adolescent girls aged 11-13 achieve greater scores on measures of formal thinking skills than pre-adolescent girls at an age of 10 and post-adolescent girls aged 14-16?

Shayer and Adey's (1993) CASE study provided evidence that adolescence may be a critical period for learning formal thinking skills. This question has not been investigated further. The Shayer and Adey study determined that the ages where the thinking skill training was the most effective was ages 11-13 for girls and 12-14 for boys, ages that match the general adolescence period for each sex. The determination of whether formal thinking skills are learned more readily during adolescence was measured using the CTSR. Student's general formal thinking skill ability as well as their ability to master specific formal thinking skills was measured. To answer this research question the data of the males and females were grouped into two groups each and compared. The males' were grouped by the ages of 12-14 (adolescence) and compared to the males aged 10-11 and 15-16 (non-adolescence). The females were grouped by the ages 11-13 (adolescence) and compared to the females aged 10 and 14-16 (non-adolescence).

<u>Male Adolescence (ages 12-14) and Male Non-adolescence (ages 10-11, 15-16) Comparison</u>

Table 4.119 and Figures 4.35 and 4.36 show the comparison between the adolescent males and the non-adolescent males thinking skills pre- and post-treatment. The data does show a difference between the two groups. The non-adolescent group has a slight increase in their thinking skill score while the adolescent group has a much larger increase. The non-adolescent males started at a higher level of formal thinking skill but after the treatment the adolescent males finished with the higher formal thinking skill score. The non-adolescent group (n = 4) gained mastery of three formal thinking skills after the intervention whereas the adolescent group (n = 3) gained mastery of four skills. The 16-year-old subject began the study as an early-transitional thinker and gained mastery of two (out of the three) of the formal thinking skills for the non-adolescent group.

Adolescent boys aged 12-14 appear to have an advantage in improving their scores on measures of formal thinking skills than pre-adolescent boys at an age of 10-11 and post adolescent boys aged 15-16.

Female Adolescence (ages 11-13) and Female Non-adolescence (ages 10, 14-16) Comparison

Table 4.117 and Figures 4.32 and 4.33 show the comparison between the adolescent females and the non-adolescent females thinking skills pre- and post-treatment. The data does not show a significant difference between the two groups. Both groups had increases in formal thinking skills scores. The non-adolescent females started at a higher level of formal thinking skill (M = 8.6) and had a slightly larger increase in formal thinking skills (+4.0) from pre-test to post-test than the adolescents (M = 6.6, +3.4). The non-adolescent group gained mastery of six formal thinking skills after the intervention whereas the adolescent group gained mastery of four skills. One of the two 16-year-old subjects began the study as a transitional thinker. Each group consists of five students. The 10-year-old subject did not gain a mastery of any new thinking skills but they did have an increase in their formal thinking skill score.

Adolescent girls aged 11-13 do not appear to have an advantage or a disadvantage in improving their scores on measures of formal thinking skills than pre-adolescent girls at an age of 10 and post-adolescent girls aged 14-16. It appears both groups of students can improve their formal thinking skills.

Comparison Of Treatment Subjects by Age and Gender

Tables 4.14-4.111 and Figures 4.1-4.28 summarize the data for the treatment subjects by age and gender. Generalizations of the data are dangerous when looking at individual students but in accord with the case study nature of this study the data of the individual students will be analyzed as general trends can be found, especially in regard to an adolescent effect in learning formal thinking skills.

The pre-adolescent males and females (Tables 4.14-4.4.27, 4.35-4.41 and Figures 4.1-4.4, 4.7-4.8) had almost no gains in formal thinking skills; the 10-year-old female had only a slight gain in thinking skills. None of the pre-adolescent students (n = 7) had mastery of any formal thinking skills before the treatment and none of the pre-adolescent student gained mastery of any formal thinking skills after the treatment.

Both the adolescent males and females had relatively large gains in formal thinking skills (Tables 4.28-4.34, 4.42-4.69, 4.77-4.83 and Figures 4.5-4.6, 4.9-4.16, 4.19-4.20). Looking at each treatment adolescent student individually, every student had very large gains in their formal thinking skill scores (minimum increase of +4 on their CTSR (24) score) except the 12-year-old female (+1 on her CTSR (24) score). Together the treatment adolescent males and females (n = 8) gained mastery of eight formal thinking skills after the treatment. Before the treatment one of the 13-year-old female students had previously mastered the control of variables thinking skill.

The post-adolescent treatment males and females had mixed results on their formal thinking skills (Tables 4.70-4.76, 4.84-4.111 and Figures 4.17-4.18, 4.21-4.28). The 14-year-old female, both 16-year-old females and the 15-year-old male all had large gains in their formal thinking skill scores. The 15-year-old female treatment student had a slight decrease in her formal thinking skill score and the 16-year-old male had no change in his score. Every post-adolescent student gained mastery of at least one formal thinking skill after the treatment, except the 15-year-old female student. Together the post-adolescent treatment students (n = 6) gained mastery of nine formal thinking skills after the treatment. Before the treatment one of the 16-year-old female students had previously mastered the control of variables thinking skill and the probabilistic reasoning skill.

The pre-adolescent treatment students were unable to improve their scores on measures of formal thinking skills or gain mastery of any specific formal thinking skills. The adolescent treatment student were able to achieve large improvements on their scores on measures of formal thinking skills as well as gain mastery of specific formal thinking skills. The post-adolescent treatment students were also able to achieve large improvements on their scores on measures of formal thinking skills as well as gain mastery of specific formal thinking skills.

Discussion

The theoretical basis of this study is the constructivist theory of learning, specifically Piaget's genetic epistemology, which asserts that learning occurs in specific stages that are passed through as a result of physical development and social interaction. According to Piaget's theory, students cannot achieve formal thinking skills until they reach adolescence. It is not known whether students who are past adolescence can obtain formal thinking skills or if adolescence is a critical window for obtaining formal thinking skills. The data from this study does not contradict Piaget's theory. The pre-adolescent males and females did not show significant gains in formal thinking skills. Although the 10-year-old female student had slight gains in her formal thinking skill scores after the treatment. She did not gain mastery of any of the formal thinking skills. None of the pre-adolescent males had a change in formal thinking skills despite the effectiveness of the treatment on other students. This evidence lends support to

Piaget's theory. There appeared to be an adolescent effect for the males but not the females. The post-adolescent female students were able to gain formal thinking skills just as readily as the adolescent female students. This was not the case for the males. The adolescent males were more successful in gaining formal thinking skills than the post-adolescent males. This may have been a result of the small number of post-adolescent males (n = 2), thus an inadequate comparison. The post-adolescent males did have some success with the treatment and were able to gain mastery of specific formal thinking skills after the treatment providing evidence for the potential of post-adolescent males to improve their formal thinking skills with appropriate instruction.

The results from this study appear to suggest that some age levels have more success learning formal thinking skills than other age groups. Generally, the results indicate that pre-adolescents are unable to learn formal thinking skills. There was not enough evidence to suggest that there is a difference between adolescents and post-adolescents in their ability to learn formal thinking skills. In fact, the data indicates that there is no difference between the adolescents' and post-adolescents' (up to 16-years-old) ability to learn formal thinking skills.

Research Question Three

3. Will students who are taught to develop their formal thinking skills in eight science class replacement intervention sessions achieve greater

scores on measures of intelligence than students of the same age who do not undergo the training?

Can inquiry-based instruction improve students' intelligence? Many believe that intelligence is determined primarily by genetics; can a research based instructional method improve students intelligence relative to the traditional method of science instruction? The determination of whether an intensive short-term formal thinking skill focused intervention program can improve students' intelligence was measured using the RPM.

Intelligence

Tables 4.9 and 4.10 summarize the pre-treatment and post-treatment comparison of the every subject's intelligence. Fourteen of the seventeen treatment students had some improvement in their intelligence score after the treatment. Two of the treatment students had a slight decrease in their intelligence score and one of the treatment students did not have a change in their score. Eight of the fifteen control students had some improvement in their overall intelligence score. Four of the fifteen control students' intelligence score remained the same and three of the control students had a decrease in their intelligence score.

Tables 4.115 and Figure 4.31 directly compare the change in intelligence of the control group to the treatment group. There is not a significant difference between the pre-test distributions of the two research groups which allows for a direct comparison of the post-test scores of the two groups. There is a significant difference between the post-test scores between the control group and the treatment group. The data indicates that the treatment did improve the intelligence of the treatment group.

Discussion

The results of this study suggest that inquiry-based instruction that focuses upon improving students' formal thinking skills may improve students' intelligence. This indicates that students' intelligence can be improved by instruction; therefore there is an environmental component to intelligence.

General Discussion

As the Educational Policies Commission proclaimed back in 1961, and is still just as valid today, many of the goals in education will be accomplished when a student's intellectual development is maximized. A student who has the ability to think has the capability to pursue his or her passions and interests. Unless a man or a woman has the ability to reason, they are not truly free; they will not be fully capable of basing their choices and actions on understandings, which they have achieved, and on values, which they have examined for themselves.

The Chapter II literature review conveyed that research in science education has found that a student's ability to understand abstract science concepts is related to his or her reasoning ability. Many entering college freshman do not have high reasoning abilities. A science course which is only focused on teaching content will often times fail in satisfying the central purpose of education; knowledge alone does not help one develop their cognitive abilities. This traditional method of science teaching typically presents students with the definitions of concepts and then they are shown the data to verify that the concept is true. Research clearly and consistently shows that this traditional method leads to students using rote memorization to learn the concepts. They do not understand how to apply the concept and thus cannot use it to solve novel problems. Students' reasoning abilities can only be developed when they are given the opportunity to apply these abilities to abstract data that must be analyzed and evaluated. It is essential that a course be taught in such a way that the students must use their reasoning skills.

An inquiry-based formal thinking skill focused instruction program appears to be an effective approach to obtaining the central purpose of education. This study indicates that students who have reached adolescence have the potential to obtain formal thinking skills.

An individual, who has the ability to reason, has the ability to accomplish their goals. He or she has the ability to prioritize their life and most importantly they have the aptitude to learn. The ability to think allows one to be free in a democratic society. A society cannot have freedom unless its citizens understand what freedom is, and thus are willing to make a commitment for it (e.g., contributing to and following its laws). Educators have the potential to give students this gift.

Conclusions

1. The results of the study indicate that formal thinking skills can be developed if they are taught using an inquiry-based approach that focuses specifically on the formal thinking skills.
2. The intervention sessions successfully helped students develop the targeted formal thinking skills: the ability to control and exclude variables, and the ability to perform proportionality reasoning.
3. The ability of students in the study to gain mastery of formal thinking skills not targeted in the intervention suggests that there is a possibility of a formal thinking skill transfer effect. Students developed formal thinking skills that were not taught to them; this provides support to Piaget's theory regarding the concrete operational to formal operational stage transition.
4. Adolescent males aged 12-14 may have an advantage in improving their scores on measures of formal thinking skills than pre-adolescent males at an age of 10-11.
5. Adolescent males aged 12-14 may have an advantage in improving their scores on measures of formal thinking skills than post-adolescent males aged 15-16.

6. Adolescent females aged 11-13 may have an advantage in improving their scores on measures of formal thinking skills than pre-adolescent females at an age of 10.
7. Adolescent females aged 11-13 do not appear to have an advantage or a disadvantage in improving their scores on measures of formal thinking skills when compared to post-adolescent females aged 14-16. It appears both groups of students can improve their formal thinking skills.
8. The results from this study appear to suggest that some age levels have more success learning formal thinking skills than other age groups. Generally, the results indicate that pre-adolescents are unable to learn formal thinking skills. There was not enough evidence to suggest that there is a difference between adolescents and post-adolescents in their ability to learn formal thinking skills. The data indicates that there is not a difference between adolescents' and post-adolescents' (up to 16-years-old) ability to learn formal thinking skills.
9. The pre-adolescent treatment students were unable to improve their scores on measures of formal thinking skills or gain mastery of any specific formal thinking skills.
10. The adolescent treatment students were able to achieve large improvements on their scores on measures of formal thinking skills as well as gain mastery of specific formal thinking skills after completing the treatment.

11. The post-adolescent treatment students were also able to achieve large improvements on their scores on measures of formal thinking skills as well as gain mastery of specific formal thinking skills after completing the treatment.
12. The results of this study suggest that inquiry-based instruction that focuses upon improving students' formal thinking skills may improve students' intelligence. This indicates that students' intelligence can be improved by instruction; providing evidence that there is an environmental component to intelligence.

Suggestions for Future Research

1. Older age groups need to be investigated to determine whether it is more difficult for individuals to learn formal thinking skills as they get older.
2. This study was relatively short term and intensive; research indicates that a longer, less intensive program would be ideal. A long-term study that seeks to answer the same research questions and includes a longitudinal evaluation to determine the long-term effects of a formal thinking skill focused curriculum needs to be completed to authenticate the research in this study.
3. A longitudinal evaluation that seeks to determine whether specific age groups have a long-term effect from a thinking skill intervention needs to be conducted. It may be the case that the gains shown in this study are temporary for some age groups while permanent for other age groups.

4. A study should be conducted to determine if there is an ideal class size or group size for a formal thinking skill intervention. Relatively small groups (n = 3–6) were used for the interventions conducted in this study. Is this the most ideal environment for such a study?

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APPENDEX A

Thinking Science Lessons

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APPENDEX B.1

Classroom Test of Scientific Reasoning

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APPENDEX B.2

Raven Progressive Matrices

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