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RELATIONSHIPS BETWEEN FORMAL-OPERATIONAL THOUGHT AND CONCEPTUAL DIFFICULTIES IN GENETICS PROBLEM-SOLVING

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RELATIONSHIPS BETWEEN FORMAL-OPERATIONAL

THOUGHT AND CONCEPTUAL DIFFICULTIES

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APPROVED FOR THE DEPARTMENT OF SCIENCE EDUCATION

By

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ABSTRACT

One hundred fifty college general biology students were taught a unit in Mendelian genetics by a traditional lecture method, using the Punnett square model for all practice problems. Students were given a unit test and, eight weeks later, a content validated post-test. Both tests required students to use proportional, combinatorial, and probabilistic reasoning in identifying gamete formations and zygote combinations. All 150 students were given the Lawson Test for Piagetian intellectual development; 71 were given Piagetian interview tasks for proportional, combinatorial, and probabilistic reasoning. Pearson correlations, factor analysis, and analysis of variance results failed to show direct relationships among Piagetian tasks for the three kinds of reasoning and their corresponding occurrence in genetics problems. Mean scores on the post-test showed significant differences among the concrete, transitional, and formal thinkers in each of the three kinds of reasoning.

RELATIONSHIPS BETWEEN FORMAL-OPERATIONAL THOUGHT AND CONCEPTUAL DIFFICULTIES IN GENETICS PROBLEM-SOLVING

CHAPTER I

INTRODUCTION

Purpose

The purpose of this study is to identify the relationships between certain aspects of formal-operational thought and conceptual difficulties related to problem solving in Mendelian genetics. Proportional reasoning, combinatorial reasoning, and probabilistic reasoning are the areas of formal thought that will be analyzed for relationships to difficulties in working with ratios from Punnet squares, gamete formation combinations, and chances of zygote formations.

Concrete-operational thought, the third stage in Piaget's developmental model, begins at about age seven and continues until formal-operational thought takes over. Piaget (Piaget, 1958) originally held that formal thought began at about age twelve for most children, but more and more researchers are finding high percentages of students still in the concrete-operational stage into their late teens (McKinnon & Renner, 1971; Haley & Good, 1976; Kolodity, 1975).

The characteristics of concrete-operational thought include the ability to perform serial ordering, correspondences, equalizations, and classifications. The term "concrete" is used to describe this stage because of the need of such thinkers to think about the objects and events of direct experience rather than abstract relationships (Piaget, 1967). The concrete thinker is able to organize thoughts about the experiences of the concrete world into usable, integrated structures that allow him to coordinate and reverse his logical operations; but he cannot perform logical operations when he is called upon to understand relationships among ideas that he cannot experience concretely.

The formal-operational level is characterized by the ability to leave the realm of objects and to function in the abstract realm of hypothetical possibilities. The formal thinker is not dependent on concrete reality in order to understand relationships among ideas, although concrete examples are certainly still very helpful. The ability to understand relationships among several abstract propositions is referred to as hypothetico-deductive reasoning (Inhelder & Piaget, 1958). The formal-operational thinker can string together abstract relationships among ideas and make judgments about them, and he can engage in reflective abstraction.

Schemata are units of cognitive structures by which the organism is able to assimilate information (Brainerd, 1978, p. 26). According to Brainerd, the formal-operational schemata necessary to solve problems involving proportions, permutations, probabilities, and correlations are more specialized than those needed to solve propositional logic problems such as implication, separation of variables, and reciprocal implication. The three areas of formal thought that will be examined in this study (proportional reasoning, combinatorial reasoning, and probabilistic reasoning) need to have their characteristics carefully examined.

Inhelder and Piaget (1958) claim that children cannot solve problems that include an understanding of ratios until they reach the formal-operational stage. Ratios are a form of proportional reasoning. In its broadest sense, the proportionality scheme "refers to subjects' understanding of the fact that the ratio of two quantities (X/Y) is equal to the ratio of two other quantities (X'/Y')" (Brainerd, 1978, p. 234). The main apparatus used in studying the ability to use proportional reasoning is the balance beam. Explanations of the use of the balance beam will be given in Chapter III, but two main rules are used by students who use proportional schemes. They first identify the need to hang equal weights equal distances from the pivot, and then they show that lighter weights must be hung further from the pivot than heavier weights.

Combinatorial reasoning is the kind of thinking that is necessary to solve permutation problems. Such problems are concerned with how many different ways a certain operation can be performed on a certain set of things (Brainerd, 1978). If a set of four things were to be arranged in all possible combinations or arrangements, then combinatorial reasoning would have been applied. Piaget used a chemical combinations test to identify children who could use combinatorial reasoning (Inhelder & Piaget, 1958). The development of combinatorial thought is an indication that formal thought has begun and is a prerequisite to the development of propositional logic (Behinaein, 1982).

Probabilistic reasoning is, according to Piaget, dependent on the development of the proportionality scheme in particular but on formal operations in general (Brainerd, 1978). Probabilistic reasoning requires a student to understand all possible events that might occur before he can understand what events are probable. The reason that concrete-operational students cannot understand frequency problems is that they involve statements of proportion.

Mendelian genetics, the basic foundation of hereditary studies is taken from the work of the nineteenth century Austrian monk, Gregor Mendel. Problem solving associated with genetics instruction is based on principles related to Mendel's three basic laws: the Law of Dominance, the Law of Segregation, and the Law of Independent Assortment.

The Law of Dominance was proposed by Mendel to explain why certain hereditary traits would mask or dominate others. This law required the hypothesis by Mendel that each organism has two factors per trait to contribute to a gamete, and that these factors may be different from each other. The dominance law will not be of particular importance in this study except for its relationship to the concept of gamete formation and separation of characters.

The Law of Segregation deals more specifically with what happens in the separation of genetic traits during meiosis. Mendel proposed that each factor for a given genetic trait had to separate to different gametes. For example, if a certain plant had both a dominant and a recessive gene as alleles on a chromosome pair, then when the plant formed gametes, via meiosis, the separating of the chromosomes would necessarily segregate the two traits. When dealing with more than one trait per organism, the possibility exists for several kinds of gametes to be produced. If a plant has both dominant and recessive genes for each of two different characteristics, there would be four kinds of gametes possible. If they were heterozygous (i.e. having both dominant and recessive genes) for three traits, there would be eight possible gamete types.

The ability to identify the kinds of gametes that would be possible according to the Law of Segregation is necessary to the problem solving process in genetics studies. The lack of ability to use combinatorial reasoning may be a major obstacle to setting up the Punnett square model for solving Mendelian problems.

The Law of Independent (Random) Assortment was Mendel's explanation of how the traits mixed randomly during segregation. An understanding of this law is also necessary to the understanding of how the total number of gametes is formed. There is a random mix of alleles from different chromosomes into a given gamete. For example, if two heterozygous traits are being considered and a dominant gene for one trait becomes a part of the make-up of a gamete, it is purely a random chance that the dominant gene for the other trait will also become a part of that gamete.

Both the segregation law and the assortment law lean heavily on an understanding of the meiotic process of gamete formation, and both laws also call upon some concept of what probabilities exist for the formation of certain gamete types. Probability reasoning is also called upon in the understanding of what offspring can result from the fertilizations among the gametes.

The Punnett square model is the most widely used approach to teaching genetics on both the secondary and college levels. The model is a grid showing symbolic representation of gametes from parent organisms on the outside and combined symbols on the inside of the grid representing fertilized eggs. These fertilized eggs (zygotes) represent the genetic traits that the offspring individuals would show. The grid represents a statistical array of gametes possible and zygotes formed. Students are generally asked to pick ratios by either appearance (phenotype) or genetic make-up (genotype) out of the Punnett square. The model can also be used to ask probability questions concerning the possibilities of appearance of a certain trait.

Pertinent Research Leading To The Need For The Study

Teachers who accept as axiomatic the idea that the central purpose of education is to develop rational thought will seriously examine both their methodology and their subject matter in the light of this purpose. Telling is not teaching, and memorization is not learning. Both of these demand recall, but the responsible teacher sees the need to devise activities that develop all of the rational powers of his students.

Since the discovery of Mendel's work in heredity in the early part of this century, biology teachers have recognized the value of basic Mendelian genetics principles to the overall understanding of life sciences. As a result, these principles are commonplace in textbooks for college introductory courses in biology, secondary biology courses, and even middle school life science courses (Rahn, 1981, pp. 556-570; Oram, 1983, pp. 116-171; Otto, Towle, & Bradley, 1981, pp. 103-125). Teachers devoted to teaching thinking rather than the mere recitation of facts have welcomed genetics to the biology curriculum as an area that involves students in problem-solving activities. However, most biology teachers who have tried to teach introductory Mendelian genetics have wrestled with the problem of why a large portion of their students do not master the ability to solve the problems. The answer may lie at least in part in the intellectual capacities of the students.

Several researchers indicate that the Mendelian genetics concepts presented in introductory biology classes require formal intellectual operations of the students. Walker, Mertens, and Hendrix (1979) proposed that combinatorial reasoning, propositional logic, and the use of probabilistic reasoning are all necessary to the understanding of many of the basic principles of genetics. Determining the equivalency of ratio and probability generation in phenotypes and genotypes requires the student to have the ability to make coordinated generalizations. This constitutes propositional logic. Walker, Mertens, and Hendrix (1979) found significant relationships between their students' scores on the Piagetian Task Instrument and their ability to solve problems requiring understanding of Mendelian genetics. The Piagetian Task Instrument contained six items equally distributed among propositional logic, hypothetical-deductive reasoning, and combinatorial logic. The other instrument was a 69-item multiple-choice test over genetics problems including Mendel's Law of Segregation, Law of Independent Assortment, dominance, incomplete dominance, epistasis, and x-linkage. The sample of students used for the study was 80 college level students enrolled in an introductory genetics course. A Pearson correlation coefficient (r) of 0.34 was calculated for the relationship between the Piagetian Task Instrument and the 69-item genetics test, allowing support to the inference of a significant relationship between Piagetian formal tasks and genetics problem solving.

Stewart (1982) conducted a study concerned with difficulties encountered by high school biology students in learning basic Mendelian genetics. He found that even students who could successfully do monohybrid cross problems could not meaningfully relate what they did in a dihybrid cross to meiosis and gamete formation. Students were able to provide acceptable definitions of most concepts used in the instruction but had difficulty describing how the concepts were related. Stewart proposed that a key difficulty which should receive attention from teachers is an algebraic problem-solving method that would allow students to see more clearly the identification of gamete genotypes.

In another study dealing with secondary school science students, Lawson and Renner (1975) found that much of the biology subject matter was aimed at the formal or abstract level. Their caution about the inappropriateness of "basic unifying themes" and other abstractions would apply at the college level if the students are concrete-operational.

Recognizing that biology consists of a complex web of inter-related concepts that may be presented to students of varying cognitive levels, Shayer and Adey (1981, pp. 98-103) analyzed a series of objectives that may appear in the curriculum for secondary students. They maintain that little understanding of genetics is possible until the early formal stage. Even the concept of chromosome separation would be inappropriate for concrete-operational students.

Smith (1983) used Piagetian interview tasks in the areas of combinatorial, proportional, and probabilistic reasoning to examine the relationship between cognitive advancement and problem-solving ability in genetics. He concluded that there was a high positive correlation between those who scored well on the Piagetian tasks and those who solved the genetics problems well; but he also stated that with a small sample containing a large number of formal-operational subjects, Piagetian tasks may not be good criteria for determining success on genetics problems.

Lawson (1979) supported the idea that genetics studies demand more formal-operational abilities than many students possess:

> Thus theoretical reasoning, combinatorial reasoning, and probabilistic reasoning, all aspects of formal thought, are involved in "understanding" and using Mendelian genetics. This analysis suggests to the developmentalist that a topic such as genetics would cause a severe comprehension problem for students with little or no facility with these aspects of formal thought (p. 511).

Most college curricula include genetics as a required subject area for general education biology courses, but a large percentage of college freshmen are not able to operate at a formal intellectual level (McKinnon & Renner, 1971; Haley & Good, 1976). A higher percentage of concrete-operational freshmen is found among those who are non-science majors (Maloney, 1981). Since general biology classes in colleges are populated mostly by those who will not be taking more specialized science courses, teachers can expect a large portion of their students to be below the formal-operational level.

If genetics problems truly do require formal intellectual abilities, there exists a serious discrepency between what many students are being asked to do and what they are able to do. More precise information needs to be gathered to clearly indicate the kinds of mental operations required of students in their attempts to solve genetics problems. Such information would be valuable in developing teaching methods appropriate to the intellectual levels of the students.

The studies by Smith (1983) and Walker, Mertens, and Hendrix (1979) were both directed, in part, at the relationships between genetics problem solving and intellectual levels. It would be appropriate at this point to identify the specific differences between this study and those. Smith used a small sample of 18, with only 9 students being given interview tasks. He was not examining the results of a large sample with a pre-test/post-test, and the hypothesis of

Piagetian stage relationship to problem solving was a minor treatment in his extensive study. Walker, Mertens, and Hendrix examined propositional logic in their study but did not consider proportional reasoning. They also differed from this study in that they used a written Piagetian Task Instrument rather than interview tasks and did not attempt to measure either proportional or probabilistic reasoning.

Hypotheses

The problem solving difficulties experienced by many students of genetics are related to their inabilities to function in certain aspects of formal thought.

1. There will be a strong relationship between a student's ability to use combinatorial reasoning and his understanding of Mendel's Law of Independent Assortment as it relates to possible gamete combinations.
2. There will be a strong relationship between a student's ability to use proportional reasoning and his ability to understand ratios of offspring as seen in a Punnett square.
3. There will be a strong relationship between a student's ability to use probabilistic logic and his understanding of chances of possible gamete and zygote formations.
4. Students who score well on Piagetian tasks will show stronger retention of genetics problem-solving

ability in a post-test.

5. A hierarchical relationship may be shown among proportional, combinatorial, and probabilistic reasoning which corresponds to a hierarchical relation to corresponding genetics problems.

Research Procedure

The plan for a more specific identification of relationships between formal thought and conceptual difficulties in solving genetics problems involved the following steps:

1. In the winter of 1983, two general biology classes at Oklahoma Christian College, each containing approximately 80 students, were given the Lawson test for formal reasoning and were scored as concrete-operational, transitional, or formal-operational according to Lawson's protocols.
2. For three weeks the classes were lectured on Mendelian genetics by the same instructor. The lecture material was traditional in content, consisting of an historical overview, meiosis and gamete formation, probability of gamete and zygote combinations, and phenotype and genotype ratios of classical crosses up through the dihybrid cross. Special emphasis was given to the Laws of Dominance, Segregation, and Independent Assortment.
3. A unit test involving objective questions and problems was given to both groups of students at the

completion of the lectures. Much of the material for this test would be classified as strictly recall, but two problems required students to identify ratios from Punnett squares, select all possible gamete combinations from a genotype, and calculate the probability of zygote combinations.

4. After eight weeks, with no additional genetics instruction, a content validated problem-solving test was given. This post-test covered the following genetics principles:
   (a) zygote formation ratios seen in Punnett squares,
   (b) the Law of Independent Assortment and gamete formation combinations, and
   (c) the probability of gamete and zygote formations.

   To eliminate the problem of forgotten terminology, a sheet of vocabulary definitions was made available with the problems.

5. In order to have data of the highest reliability concerning intellectual development, 71 of the students were given Piagetian task interviews over proportional reasoning, combinatorial reasoning, and probabilistic reasoning. These interviews were conducted within two weeks of the administration of the post-test. The balance beam task for

proportional reasoning was used in the interviews. Protocols for this task were established by Inhelder and Piaget (1958). The electronic switchbox task (DeLuca, 1979) was used to measure combinatorial reasoning. Probabilistic reasoning was measured by the use of colored squares and diamonds with protocols adapted in part from the Lawson Test and suggested by Shayer and Adey (1981). Protocols for all three tasks are discussed in detail in Chapter III.

6. Results from the four different sources of information (unit test, post-test, Lawson Test, and interview tasks) provided data for statistical analysis of the relationship among the three areas of formal thought and conceptual difficulties in genetics problem solving. Results of each test were broken down into categories of proportional, combinatorial, and probabilistic reasoning. Pearson correlation coefficients were sought for the three categories plus the overall results of each of the four tests. Mean scores were calculated for the three categories and overall score of each of the four tests, with attention to students who scored in the concrete-operational range, the transitional range, and the formal-operational range. ANOVAs were used as tests of significance for the mean

scores for the different groups. The occurrence of correct and incorrect answers was calculated for each student on both the unit test and the post-test to identify any unusual pattern of responses. Factor analysis was used to try to identify hierarchical relationships among reasoning types.

Analysis of these statistical treatments provided information concerning the relationships between formal thought and problem-solving in genetics. The hierarchical relationships among proportional, combinatorial, and probabilistic reasoning were studied in order to search for meaningful directions for pedagogical approaches in this important subject area. Much of the biological sciences taught at the introductory level is so "facts" oriented that areas which provide a chance to develop important concepts should not be discarded but should be re-examined in the light of the intellectual abilities of the students. It is hoped that this study will make a contribution to that re-examination.

CHAPTER II

RELATED LITERATURE

Jean Piaget's work in cognitive development has had a strong impact on educational research in the past two decades. Due to Piaget's influence, new questions have been asked by researchers and curriculum designers about the appropriate time to introduce topics into a student's educational experience. Much effort has gone into examination of the cognitive demands of various courses to assure that the material in offered coursework is properly aligned with the intellectual development of the student. Of primary concern, then, is the proper identification of the student's intellectual development.

Cognitive Development

Piaget has described intellectual development in terms of four stages (Inhelder & Piaget, 1958). The first two stages, called sensory-motor and preoperational, are usually completed by the time a child reaches seven or eight years of age. The last two stages are stages of logical operation, called concrete-operational and formal-operational; and these are the relevant stages for consideration to the secondary and college teacher.

According to the Piagetian model, students reach a state of formal-operational thought at about age fifteen or sixteen after having begun to enter that stage of cognitive development at age eleven or twelve. Much recent research indicates, however, that many secondary students past the age of fifteen cannot be expected to operate in the formal realm. Studies show that 40 to 75% of students in the secondary schools have not yet reached the formal-operational intellectual level (Renner & Stafford, 1973, pp. 291-296; Lawson, Karplus, & Adi, 1978; Lawson & Renner, 1975; Chiapetta, 1976). A large number of college level students have also been shown to be at the concrete-operational level of cognitive development. McKinnon and Renner (1971) used five Piagetian tasks to examine the cognitive development of college students in a variety of colleges in Oklahoma. They found that approximately 50% of the students tested were concrete-operational thinkers. In a study of 143 freshmen students in a private university Lawson and Renner (1974) found 51% at the concrete-operational stage.

Maloney (1981) found that the percentage of incoming science majors who tested as concrete-operational at Creighton University was low (below 18%). However, 50% of those students who were non-science majors and in a minority program proved to be at the concrete intellectual stage.

Recognition of the intellectual level of the learner is of great importance in education (Haley & Good, 1976). In the past there has been very little agreement among educators on the nature of the learning process. Curriculum changes have often been made for the sake of change itself. If educators listen carefully to the basic tenents of what Piagetian theory says about the learner, they will recognize that it is not only important for the curriculum to start with what the student knows but with what the student has the intellectual capacity to learn (Kolodity, 1975). Lawson and Renner (1975, p. 357) said, "Whichever direction schools choose to take. . .the intellectual level of the learner should become a major consideration in curriculum reform." These researchers found that approximately 65% of high school biology students were entirely or partially concrete-operational. This was particularly disturbing since most of the subject matter was either formal in content or presentation. Concerning the plight of concrete-operational students in a formal-operational course, they said, ". . .it appears that for them a science course which deals with abstractions and 'basic unifying themes' is inappropriate" (Lawson & Renner, 1975, p. 356).

Complex explanations given in science courses are a vital part of presenting ideas of natural phenomena. Bass and Maddux (1982) found that concrete-operational students in both high school and college settings may be able to chain together two implication statements as well as formal-operational students but that when three or four statements of implication are used in a sequence the formal students do significantly better.

Attention needs to be given to the actual content material used in science instruction to identify it as either concrete or formal in nature. Concrete instructional methods have proven superior regardless of whether or not the students instructed are formal. Research in this area indicates the need for a change from the "exposition" method of teaching, which is basically formal, to the "inquiry" method, which lends itself more readily to using concrete concepts (Schneider & Renner, 1980). Terminology may represent concepts that can be concrete according to one meaning but formal according to another. Karplus (1977) warns that teachers need to remember to be specific about how a concept is used in order to keep from forcing a formal concept upon students not capable of understanding it. Some concepts are always formal. As Karplus says,

> . . ."gene," "chemical bond," "periodic system," and "ideal gas"--all require formal reasoning patterns for their understanding. They can only be defined in terms of other concepts, abstract properties, theories, and mathematical relationships. There is no way of defining them as "concrete" concepts (Karplus, 1977, p. 173).

Lawson and Renner (1975) define concrete concepts as those concepts that can be developed from first-hand experience with objects or events or that may be postulated because part of the meaning of the concept can be immediately sensed. Examples they cite include recognition of common objects such as a table and chairs or the color blue. Formal-operational concepts are those ideas that depend on a postulatory-deductive system for understanding. Students who are able to comprehend formal-operational concepts can do so without depending on first-hand experience but need only to rely upon their imagination or logical relationships for understanding.

When students are presented with formal-operational concepts in the classroom, it is necessary for them to have formal-operational schemata to be able to deal with those concepts. Inhelder and Piaget described the characteristics of formal schemata in the following way:

> Now, the outstanding feature of the data of the empirical investigation was that they showed that formal thought is more than verbal reasoning (propositional logic). It also entails a series of operational schemata which appear along with it; these include combinatorial operations, propositions, double systems of reference, a schema of mechanical equilibrium (equality between action and reaction), multiplicative probabilities, correlations, etc. (Inhelder & Piaget, 1958, p. xxii).

The particular types of formal-operational thought of interest in this study (proportional reasoning, combinatorial reasoning, and probabilistic reasoning) have all been recognized as being a part of the schemata that a truly formal-operational student possesses. As various researchers have sought to develop measures of formal thought that are less time consuming than the Piagetian interviews, they have often included these types of reasoning in their pencil-paper or demonstration tests (Walker, Hendrix, & Mertens, 1979; Shayer & Adey, 1981).

The understanding of proportional relationships in the offspring of genetic crosses is a commonly studied part of Mendelian genetics, yet many students have great difficulty picking the ratios from a Punnett square. Arons (1983, p. 567) said, "One of the most severe and widely prevalent gaps in the cognitive development of students at secondary and early tertiary level is the failure to have mastered reasoning involving ratios."

Walker, Hendrix, and Mertens (1979, p. 212) stated, "The generation of all possibilities (combinatorial logic) requires operation in the hypothetical realm or the manipulation of propositions rather than objects." They included combinatorial tasks on their written Piagetian Task Instrument, recognizing the necessity of including permutations as a measure of formal-operational thought.

Lawson, Adi, and Karplus (1979) investigated ways that high school biology courses help develop correlational reasoning in students. They concluded that it does not appear that correlational development is enhanced by the study of high school biology but that since correlational reasoning may in fact depend on a previous understanding of probability and proportions it may be effective to integrate the mathematics and science curriculum to connect the theoretical and empirical work. The study of genetics does help integrate mathematics principles with theoretical biology and should not be overlooked as a way of using the curriculum in biology to enhance intellectual development. However, ways must be found to adapt instruction to the level of reasoning seen in the students.

There is a very close relationship between the areas of combinatorial and probabilistic reasoning. Piaget and Inhelder (1975) state that combinatorial reasoning preceeds probabilistic: "But above all, the achievement of probabilistic notions implies the ability to use combinatoric operations--combinations, permutations, and arrangements" (p. 160). Piaget (Piaget & Inhelder, 1975) placed probabilistic thought squarely in the formal-operational stage:

> In stage III, finally, the intuitions cease to be global, and the refinement of the idea of chance and the calculation of probabilities are conceived of as fractions of certainty related to the totality of possible combinations (p. 130).

Fischbein (1975) holds that there are as yet undetermined intuitive sources of dealing with probability shown by children, but he agrees with Piaget that there is the necessity of entering formal-operational thought before the concepts of fraction chance of the whole can be comprehended.

Genetics As The Realm Of Study

Hickman, Kennedy, and McInerney (1978) assessed high school, junior, and senior college instructors concerning current needs in genetics education. They reported that most teachers saw the areas they were already teaching as being most important, and this almost always included basic Mendelian principles. The most highly recommended change was the need for increased instruction in principles of human genetics. Haddow (1982) reported on a program to present material on all aspects of human genetics to high school biology teachers. She commented on the need for high school students to have a good basic knowledge of human genetics before graduating.

Although the value of genetics studies has been widely supported, there remains relatively little research analyzing the cognitive skills needed to effectively master the concepts. Stedman (1973) used a 92-frame genetics program of behavioral objectives trying to determine if the four levels of educational taxonomy are arranged hierarchically. He found no significant results between knowledge and comprehension. Cannon and Simpson (1980) studied the relationship between success in a genetics course and two measures of self-concept. Anderson and Fowler (1978) used the Cornell Critical Thinking Test and variously arranged Bloom's behavioral objectives to analyze the learning of college students in a unit on population genetics. Although these studies certainly have some value, they did not address the specific area of cognitive development and genetics studies.

Stewart (1982a) researched the difficulties of high school students in learning basic Mendelian genetics by using a think-aloud study with ninth-graders. The students were given 100 questions involving monohybrid and dihybrid crosses, and the results showed surprisingly few missed problems. However, many students demonstrated an inability to explain their solutions. Stewart maintained that the students' lack of understanding of meiosis and its relation to genetics was the problem and not the inability to generate combinations, i.e. combinatorial reasoning. He presented no data concerning the intellectual level of the students, nor did he discuss the idea of formal operations required in genetics. In a later study Stewart (1982b) proposed a model that would include procedural steps used in arriving at the solution of a genetics problem and the conceptual knowledge of both meiosis and genetics that would allow the problem solvers to justify what they have done. It would seem that in both studies Stewart would have more direction if he employed a developmental theory base that might offer some specific measure of the students' logical abilities in areas outside of the specific concerns of genetics.

In studies with college students, Walker, Hendrix, and Mertens (1979) correlated students' success in solving Mendelian genetics problems with their level of Piagetian development. Correlation coefficients ranged from .36 to .21 over the Piagetian tasks of combinatorial, probabilistic, and propositional reasoning. These same researchers claimed significant gains in the abilities of students using their

Piagetian-based programmed instruction guide of sequenced instruction in genetics (Walker, Hendrix, & Mertens, 1980). The sequenced instruction in this study did not follow any well-researched form of Piagetian based instruction, and there was an absence of control groups.

Smith's study (1983) examined the relationship among proportional, combinatorial, and probabilistic reasoning and success in genetics problem solving in college students and college teachers. The small sample of eighteen, with only nine students taking the Piagetian tasks, presents a problem to statistical analysis of the relationship between formal thought and problem solving in genetics. Smith found that the most difficult aspect of genetics problem solving was dealing with elementary probability and that this was true even for those subjects who had little difficulty with probability in the Piagetian task. However, he proposed that it would be inappropriate to avoid the teaching of elementary probability. Smith recommends that teachers be careful to use the Punnett square as a model that shows probabilities rather than "individuals." Although investigating formal thought and how it influences problem solving ability was only a small part of Smith's study, he concluded

> Formal operational thought was clearly demonstrated to be an insufficient condition to determine problem-solving success. Successful manipulation of genetic combinations by non-formal subjects was also observed suggesting that the formal operational schema of combinations may be an unnecessary condition to successfully solving the selected problems as well (p. 237).

Perhaps a larger sample of students of varying intellectual development, such as are typical in an introductory college course, would have prompted a different conclusion.

Lawson (1982) indicated that a concrete-operational student on the college level may well be able to respond significantly better to instruction than a seventh grade student who is also concrete-operational. The college student may have a greater capacity to process information, or the background of more experience may allow him to function better than the seventh grade student.

As educators decide what content material is appropriate for instruction at various grade levels, it should be noted that stage development may not be the only consideration; however, the research cited here offers considerable evidence that some important curriculum and instruction findings are tied to students' intellectual levels. This study investigates whether or not relationships exist between students' formal abilities in proportional, combinatorial, and probabilistic reasoning and their success with genetics problems involving corresponding reasoning types.

CHAPTER III

METHODOLOGY

To appropriately address the hypotheses stated in Chapter I, the methodology used must accurately measure the intellectual level of each student. Testing of students' abilities in genetics problem solving should be aimed at analyzing the specific areas of proportional, combinatorial, and probabilistic reasoning by using Mendelian problems that call for offspring ratios to be recognized and gamete combinations and probabilities to be described. To identify the retention abilities of students of different intellectual levels, a reliable post-test needed to be developed.

Preliminary Study

In an attempt to discover relationships between students' Piagetian level and their difficulties in solving genetics problems, a preliminary study was done in the fall of 1982. A sample of 45 students in a general biology class at Oklahoma Christian College were given the Lawson Test (Lawson, 1978) to determine abilities in formal reasoning. This 15-item demonstration test grouped the students into concrete-operational, transitional, and formal-operational categories. In this sample 28% were concrete-operational, 57% were transitional, and 15% were formal-operational. After three weeks of lectures on basic principles and problem-solving in Mendelian genetics, a unit test was given. The test was a mixture of objective questions and problems. Eight weeks later a problem-solving and discussion question test was given. Both tests included problems related to proportional, combinatorial, and probabilistic reasoning that required students to analyze gamete formations and zygote combinations. Results of this study indicated that much of the material was memorized for the first test and that true understanding of the material was lacking. While students were able to answer objective questions related to terminology with a high degree of success, they were generally unable to apply the terminology to problems. There was no significant difference in the performances of the different Piagetian stage groups. However, there was a strong relationship between those who scored in the formal-operational level on the Lawson Test and those who showed good problem-solving skills on the follow-up exam. The mean score for formal-operational thinkers was 82.3%, while the means for transitional and concrete-operational students were 79.6% and 55.6%, respectively.

Subjects

The preliminary study pointed out the need for a more careful design and analysis of the intellectual abilities of the students and their relationship to genetics problem solving. The subjects for this study were students in general biology classes at Oklahoma Christian College during the winter term of 1983. General biology is a required general education course for all students who are not majoring in biology. Classes are comprised mostly of freshmen, with a few upperclassmen. In the sample of two large classes used in this study, there were 124 freshmen and 26 upperclassmen. Of those who were given the task interviews on proportional, combinatorial, and probabilistic reasoning, 62 were freshmen; 9 were upperclassmen. Only one of the upperclassmen was as old as 22 years. The entire study group was comprised of 68 males and 82 females, with 35 men and 36 women making up the sample that were interviewed for intellectual development. Each lecture section numbered approximately 80 students when the instruction on genetics began. Shrinkage from the course reduced the total sample to 150 by the time the post-test was administered.

Volunteers were sought for the interview tasks. Students who had taken the unit test, the post-test, and the Lawson Test were asked to make an appointment for 30 to 45 minutes of "non-threatening" (not related to course grade) testing during the last three weeks of the term. Appointments were made on a sign-up sheet on the office door of the instructor. No attempt was made to select interview subjects from the results of the Lawson Test. The Lawson

Test was used primarily to assure that the sample given interviews was typical of the students taking the course. It showed the sample to be a good mixture of the developmental levels seen in the course.

The Lawson Test

The Lawson Test was administered separately to the two large lecture sections immediately before the unit lectures began. The 15 items were demonstrated as described by Lawson (1978), and the scoring of written responses was done according to his protocols. Nine items on the Lawson Test relate directly to the areas of proportional, combinatorial, and probabilistic reasoning. The scores on these items were tallied as a separate result for possible useful comparison with the interview tasks' results. The overall student score on the 15 items determined placement into the categories of concrete, transitional, or formal-operational reasoning (0-5 correct indicates concrete-operational, 6-11 indicates transitional, and 12-15 correct indicates formal). The overall score on each of the 15 items was tallied for each student for statistical comparison with scores on items of a similar nature on the other instruments used in this study.

The Unit Test

The unit objectives given to the students and used as a guide for the lectures can be seen in Appendix A. This researcher lectured both sections of students with each group meeting separately for nine 50-minute lectures over a three week period. The Punnett square approach to problem-solving was used in all of the lectures. Sample problems assigned as homework during the presentation of the material and a description of the daily lecture schedule may also be seen in Appendixes B and C.

Genetics problems that are traditionally part of the unit exercises in general biology classes consist of stated genotypes of parent individuals that are to be crossed with each other. The student must decide what kind of gametes can be formed from each genotype and then place the symbol for one of each gamete type on the outside of a Punnett square. For example, if the genotype for an organism were AaBb, then four gametes would be formed: AB, Ab, aB, and ab. The Punnett square is completed by combining the symbols from the top and sides in the internal boxes of the square. Students are typically asked to pick the genotype and phenotype ratios from the Punnett square. The genotypes within the square represent a proportional model of new zygote combinations. Figure 1 shows an example of a Punnett square for a cross between an organism heterozygous for two traits and a homozygous organism.

FIGURE 1

PUNNETT SQUARE

AaBb x AAbb

	AB	Ab	aB	ab
Ab	AABb	AAbb	AaBb	Aabb

The unit test contained two questions calling for students to identify the combinations of gametes and the ratio of offspring but only one probability question. The questions forming the unit test were

1. In garden peas, tall (T) is dominant over short (t). Illustrate, with a Punnett square, a cross between two heterozygous tall pea plants and state the genotype ratio.
2. In some rabbits, long hair (L) is dominant over short hair (l); and brown color (B) is dominant over white (b). Cross a rabbit that is heterozygous for both traits with one that is short-haired and heterozygous brown. Show a Punnett square for the cross and state both the phenotype ratio and the probability that an offspring will have only recessive genes.

The unit test, in the form given to students, may also be seen in Appendix D. It was administered at the end of the nine lecture sessions. A score of zero was assigned for an incorrect answer, while a score of one was given to a correct answer. As a result, scores ranged from 0-5 for the unit test.

The Post-Test

Validation of a written test for the areas of genetics that call upon proportional, combinatorial, and probabilistic reasoning required the assistance of experienced professors in the field of genetics. The post-test problems were presented to three teachers with a request that they judge the validity of the problems in measuring the simple Mendelian genetics problem solving skills in question. The test was approved by Dr. James Thompson, a professor of genetics at the University of Oklahoma; Dr. Warren Smith, chairman of the biology department at Central State University; and Dr. Darvin Keck, a genetics teacher at Oklahoma Christian College. These consultants offered helpful suggestions about the wording of the problems and agreed that the six items on the test did measure a student's ability to find gamete combinations from a given genotype, to identify ratios from a Punnett square, and to describe the probability of a gamete or zygote formation.

The following questions made up the post-test:

1. Using T for tall (dominant over t, short) and G for green (dominant over g, yellow), from the following Punnett square give the phenotype ratio.

	TG	Tg	tG	tg
TG	TTGG	TTGg	TtGG	TtgG
Tg	TTGg	TTgg	TtGg	Ttgg

2. From the following Punnett square, give the genotype ratio of the offspring.

	RP	Rp	rP	rp
Rp	RRPp	RRpp	RrPp	Rrpp
rp	RrPp	Rrpp	rrPp	rrpp

3. List the gametes with different genetic traits that could be formed by an organism that possessed the following gene combinations: Bb RR Nn Hh ss.
4. An organism that is heterozygous for one trait (i.e. having both dominant and recessive genes) and homozygous for another trait (i.e. having only the dominant genes) makes gametes. Considering only these two traits, how many different kinds of gametes could this organism produce? (List them)
5. An organism has the genotype Mm RR Tt. What are the chances that a gamete formed from this organism will have at least one recessive gene?
6. A plant is heterozygous Aa Bb. The genes are inherited according to the Law of Independent Assortment. Find the probability that an ovum will contain an "A" gene and a "b" gene.

Guidelines used for scoring the post-test were as follows:

1. Each of the first two items was judged to be correct if the correct phenotype or genotype ratio was indicated.
2. Items #3 and #4 were both judged to be correct if all of the gametes that could be formed were listed once and only once.
3. The last two items were judged to be correct if the proper probability was expressed as a fraction or

ratio or was described correctly by a statement such as "one out of four."

For ease of statistical analysis, the value of zero was assigned for each incorrect answer and a value of one for each correct answer. Scores on the post-test ranged from 0-6. The post-test was administered eight weeks after the unit test. As the test was administered, students were reminded of the availability of a vocabulary list that defined all of the genetics terms that were on the post-test. The vocabulary list was provided to eliminate the variable of forgotten terminology and can be seen in Appendix E.

The Interview Tasks

Video tapes were made of this researcher administering the three interview tasks to four students. Dr. Michael Abraham and Dr. John Renner (both of the University of Oklahoma) viewed the video tapes and gave advice about the protocols used and the scoring decisions made. As the interviews were conducted with the 71 volunteers from the two classes, notes were taken on student responses; and audio tapes were made of the interviews. The tapes provided clarification of the responses made by students as the three tasks were scored.

The Balance Beam Task

The balance beam task was used to investigate the proportional reasoning abilities of the students. Protocols for this task were established by Inhelder and Piaget (1958). The students were shown that the beam would balance and that it had 14 evenly-spaced hooks on each side. Students were then told that the interviewer would place weights on one side of the beam and that they would be asked to use a single weight or weights hooked together to balance the beam. Each time the students hung weights, the hooks were counted aloud. As students made decisions and hung their weights, the interviewer held the bar, not allowing the effect of the weights to be seen until he had asked, "Why did you decide to hang the weight where you did?"

A series of five exercises was used to see how each student used proportional reasoning to decide where weights should be hung:

1. The interviewer hung a 100 gram weight on hook #6. The student was asked to balance the beam with another 100 gram weight.
2. The 100 gram weight was again placed on hook #6, and the student was asked to hang two 50 gram weights to balance the beam.
3. With the 100 gram weight still on hook #6, the student was asked to balance the beam by hanging a single 50 gram weight.
4. The interviewer then placed 120 grams on the third hook and asked the student to balance it with 40 grams.

5. Finally, 70 grams was hung on hook #10, and the student was asked to balance it with 100 grams.

If there was uncertainty on the part of the interviewer about whether or not the student was truly using proportional reasoning rather than an algorithm, a sixth item was used. It consisted of hanging 60 grams on hook #6 and asking the student to balance the beam with a 40 gram weight.

Scoring of the tasks followed the guidelines suggested by Renner, et al. (1976, p. 9).

1. Early concrete students (IIA) were unable to successfully answer any item beyond Step Two.
2. Late concrete students (IIB) were successful up through Step Three with the inclusion of an explanation of the proportion concept.
3. If students were able to answer Step Four correctly and include an explanation of proportions, then they were classified as early formal (IIIA).
4. Late formal students (IIIB) were successful in balancing all of the weights and in giving an explanation of the proportions concept.

The Electronic Switchbox Task

The electronic task (DeLuca, 1977) has been proven to be a valid test of a student's ability to use combinatorial reasoning. It imitates the reasoning required by Piaget's chemical combinations task (Inhelder & Piaget, 1958). The equipment consists of a metal box with four toggle switches, a push-button, and a battery-operated light. As various combinations of switches are turned on, the push-button may be pushed to determine whether or not a particular combination of switches will allow the light to come on. Switches #1 and #3 are both required to be in the "on" position for the light to come on. Switch #2 is not connected at all, so combination #1, #3, and #2 will also light the bulb. Switch #4 is an inhibitor switch and will not allow the light to be lit with any combination.

The box was given to each student with the explanation that the four switches have "off" and "on" positions and that the light would not be lit until the push-button was depressed. The student was then asked to work with the switches and find as many ways as possible to light the bulb. When the student stopped working with the switches, he was asked if he had tried all possible combinations. He was then asked specifically about the roles of switches #1 and #3. Students were then asked to explain the roles of switches #2 and #4. Careful attention was given to the verbal answers given by the students and to the way in which they explored the possible combinations of "on" switches.

Scoring of the task followed the procedure described by DeLuca (1979) and Behinaein (1982).

1. Early concrete students (IIA) tried switches singly or all four together. They attributed the light's

being turned on to a single switch. They would not try groups of two or three switches in any orderly fashion.

2. Late concrete students (IIB) tried two or three switch combinations but in a random pattern. They also attributed the light control to one switch.
3. Early formal students (IIIA) used a systematic approach to trying two and three switch combinations. They recognized the fact that the light control should be attributed to more than one switch. They proceeded until they had tried all possible switch combinations.
4. The late formal students (IIIB) tried all combinations in a rapid, organized fashion. They understood the role of all switches and could prove the roles by demonstration.

The Probability Task

Protocols and scoring for probability tasks are not as well established as for the Balance Beam Task and the Electronic Task. Lawson (1978) used colored squares and diamonds in the probability items of his group test, and Shayer and Adey (1981) referred to the ability of late concrete and early formal subjects to predict chances of drawing colored objects out of a bag. In this study the protocols for the probability tasks were as follows:

1. The student was instructed to shake two yellow squares and two blue squares in a covered box. The interviewer asked, "What are the chances of your drawing a blue square on the first draw?"
2. The student was instructed to shake a box containing one each of red, blue, and yellow squares and two each of red, blue, and yellow diamonds. The interviewer asked, "What are the chances of your drawing a square of any color on the first draw?"
3. The student was asked to shake a box containing 5 blue squares, 4 yellow squares, 3 red squares, 3 blue diamonds, 2 yellow diamonds, and 4 red diamonds. The interviewer asked, "What are the chances of your drawing a red piece (either a square or a diamond) on the first draw?"
4. Using the same items as in number 3, the interviewer asked, "What are the chances of your drawing a blue diamond on the first draw?"
5. Using a partition in the box and putting 1 red, 2 yellow, and 3 blue squares on one side and 3 red, 2 yellow, and 1 blue squares on the other, the interviewer asked, "What would be your chances of drawing a yellow square from each side at the same time on the first trial?"

Scoring of probabilistic reasoning was based on correct answers for each item and an explanation of how the correct answer was derived. If a student expressed an answer as a fraction and could not give the reason why that fraction was used, then that particular item was not scored as correct. For example, one student made the statement, "The way you do these kinds of problems is to make a fraction with the total items on the bottom and what you want on the top, and sometimes you have to reduce the fraction." If the student had no explanation of why the fraction was needed, it was assumed that he had memorized a technique for solving probability. Students were scored as follows:

1. If a student could not answer any of the probability questions, he was scored as early concrete (IIA).
2. If only the first item was correctly answered, the student was considered late concrete (IIB).
3. Students who correctly answered all of the first four problems and were able to explain why they chose the answer were scored as early formal (IIIA). A typical explanation for why a certain probability was chosen was given by one student: "There are seven things you want, but there are twenty-one things altogether. Since you might grab any of the twenty-one things, then the chances are seven out of twenty-one, or one in three."
4. Late formal students (IIIB) were able to answer all five items correctly with explanation.

Students were scored as IIA, IIB, IIIA, or IIIB on each of the three interview tasks. For ease of statistical usage, these four categories were assigned values of 1, 2, 3, and 4, respectively, according to the method used by Renner (1979, p. 281). Since none of the 71 subjects interviewed was scored below the IIA level in any of the three tasks, the total score for each student ranged between 3 and 12. For comparison with the Lawson Test, students needed to be grouped as concrete, transitional, or formal. Only students who scored IIA or IIB on all three tasks were considered concrete. Transitional students were those who scored formal on one or two of the tasks but concrete on at least one. Formal students were those who scored IIIA or IIIB on all tasks.

Statistical Analysis

Each of the instruments used in this study (unit test, post-test, Lawson Test, and the Piagetian interview tasks) related to the areas of proportional, combinatorial, and probabilistic reasoning. Raw scores and patterns of right and wrong answers were examined to determine whether or not there were particular occurrences of answers that related specifically to one of the three areas of formal thought considered.

Mean scores were calculated for the performances of the students on all four instruments. Trends seen in the means for concrete, transitional, and formal students in the areas of proportional, combinatorial, and probabilistic reasoning are discussed in Chapter IV. Pearson correlation coefficients were calculated for the group of 71 interview students with each category of formal thought in each of the instruments. Correlations were also found for the overall scores in each category. Analysis of variance was done on the scores of the different instruments, with Tukey's Studentized Range test used for post hoc analysis. Factor analysis was done on the combination of post-test and interview task scores.

Summary

The sequence of methods for this study may be summarized in the following steps:

1. The sample of 150 students were administered the Lawson Test for intellectual development.
2. Nine 50-minute lecture and problem solving sessions on Mendelian genetics were held over a three week period.
3. A unit test was administered that called upon students to solve problems that dealt with the Law of Segregation, the Law of Independent Assortment, and probabilities of gamete formation. This test followed immediately upon the completion of the instruction period.
4. Eight weeks after the unit test was completed, a post-test was administered. This test covered the same problem solving areas as the unit test, and a vocabulary list was supplied the students as they

took the test.

5. A sample of 71 volunteer subjects who had taken both tests were administered Piagetian interview tasks in the areas of proportional, combinatorial, and probabilistic reasoning.

CHAPTER IV

RESULTS

Two instruments were used to assess the intellectual development of the subjects for this study. The Lawson Test's 15 items were demonstrated for the entire sample of 150 students, and the three Piagetian interview tasks were then administered to 71 of the 150. A unit test and a post-test were the instruments used to measure the students' genetics problem solving ability. The results of each test will be presented separately followed by data relating the various instruments.

The Lawson Test

The Lawson Test provided two major aids to this study. First, it gave assurance that the sample of students did indeed show a good mixture of intellectual levels that might be examined appropriately for the hypotheses under consideration. Secondly, the Lawson Test would help provide some reassurance that those given the Piagetian interview tasks were not atypical of the students found in college general biology classes.

TABLE 1

LAWSON TEST SCORES

(N=150)

Test Item	Mean	S.D.
L1 Conservation of mass	.70	.46
L2 Conservation of volume	.75	.44
L3 Proportional reasoning	.73	.44
L4 Proportional reasoning	.59	.49
L5 Proportional reasoning	.81	.40
L6 Proportional reasoning	.58	.50
L7 Separation of variables	.82	.39
L8 Separation of variables	.83	.38
L9 Separation of variables	.47	.50
L10 Separation of variables	.55	.50
L11 Combinatorial reasoning	.49	.50
L12 Combinatorial reasoning	.43	.50
L13 Probability reasoning	.59	.49
L14 Probability reasoning	.43	.50
L15 Probability reasoning	.41	.49

The mean scores seen in Table 1 indicate that two of the three areas of reasoning chosen for this study, combinatorial and probabilistic reasoning, are the most difficult of the tasks included in the Lawson Test. The scores on the last five items of the test are considerably lower and indicate that much of the separation into intellectual levels may have been determined by these items.

TABLE 2

INTELLECTUAL LEVELS AS DETERMINED BY LAWSON TEST

	(N=150)		(N=71)	
Intellectual Level	Number	%	Number	%
Concrete-operational (0-5 correct)	23	15.3	16	22.5
Transitional (6-11 correct)	83	55.3	37	52.1
Formal-operational (12-15 correct)	44	29.3	18	25.3

Table 2 illustrates the results of the Lawson Test by separation into intellectual levels. The scores for the group of 71 were lower than for the entire group of 150. The most notable difference was the higher number of concrete students in the group of 71 (22.5%). Although the interview tasks were on a volunteer basis, it may have been that students who were not doing as well in the course decided to volunteer with hope of receiving some consideration for a higher grade. If this were an explanation for the lower scores of the interview group, it would be based on the assumption that there is some relationship between lower intellectual development and lower course grades.

The Interview Tasks

The Piagetian interviews were given over the specific intellectual areas of proportional, combinatorial, and probabilistic reasoning. These tasks were administered only to the 71 volunteers that had participated in all of the other activities of the study and provided a more precise measure of the problem solving skills possessed by the genetics students.

TABLE 3

RESULTS OF PIAGETIAN INTERVIEW TASKS

(N=71)

Task Item	Mean	S.D.
T_1 Proportional Reasoning (balance beam)	2.11	.92
T_2 Combinatorial Reasoning (electronic switch-box)	2.44	.69
T_3 Probabilistic Reasoning (colored squares & diamonds)	2.66	.67

The balance beam task for proportional reasoning proved to be the most difficult task as is shown by Table 3. Probability reasoning scores were the highest of the three tasks. The interview task results by category of proportional reasoning, combinatorial reasoning, and probabilistic reasoning are shown in Table 4. The number of students that scored in the IIA (early concrete), IIB (late concrete), IIIA (early formal), and IIIB (late formal) categories, according to the protocols described in the previous chapter, are indicated.

TABLE 4

NUMBERS OF STUDENTS IN PIAGETIAN LEVELS

	Proportional reasoning	Combinatorial reasoning	Probabilistic reasoning
IIA (early concrete)	18	3	0
IIB (late concrete)	35	39	32
IIIA (early formal)	10	24	31
IIIB (late formal)	8	5	8

As previously described, the students were assigned numerical values ranging from 3 to 12 for ease of statistical analysis and to place them into the three categories of concrete, transitional, and formal thought. Table 5 shows how such a treatment placed the 71 students into the three categories.

The results of the 71 interviews showed that more students were concrete-operational according to the Piagetian tasks (28) than according to the Lawson Test (16). The Lawson Test and other group-type demonstration tests or pencil-paper tests of intellectual development do not usually tend to be as discriminating as the Piagetian interview tasks (Lawson, 1978). It seems that in this study the interviews

TABLE 5

INTELLECTUAL LEVELS AS DETERMINED

BY PIAGETIAN INTERVIEW TASKS

(N=71)

Intellectual Level	Number	%
Concrete-operational	28	39.4
Transitional	27	38.0
Formal-operational	16	22.5

forced the evaluation of several students downward. Compared to the Lawson Test results, 12 students moved downward to the concrete level; and two moved from formal down to transitional after taking the interviews. No student moved from formal to concrete or from concrete up to formal.

The most notable feature of these results is the apparent difficulty that this sample of students had in the area of proportional reasoning. Fewer students (18) scored in the formal level on the proportional reasoning tasks than on the combinatorial tasks (29 students) or the probabilistic tasks (39 students). According to data to be presented later in this chapter, these students did not score well on probability questions in genetics problems. The high score in probability tasks may be attributable to the use of algorithms learned in introductory mathmatics classes. Since the majority of the students in this study were second semester freshmen, many may have retained techniques for solving both permutations and probability from a recent course. A more likely explanation is that the protocols for the probability task are not clearly enough established to be a good measure of a student's true understanding of probability.

Arons (1983) indicated that students' understanding of ratios and proportions is one of the most seriously deficient aspects of cognitive development in late high school and early college ages. The results in this sample would seem to bear out that position.

A one-way analysis of variance was done on the scores of the interview tasks as a test of significance. The ANOVA indicated significant differences among the task items as shown in Table 6.

TABLE 6

ANALYSIS OF VARIANCE FOR INTERVIEW TASK SCORES

Source of Variation	DF	Mean Square	F	P
Interview Tasks	2	5.413	9.13	.0002

POST HOC ANALYSIS

TUKEY'S STUDENTIZED RANGE TEST

(Means with same letter not significantly different)

Item	Mean	Tukey Grouping
Task 1 (proportional)	2.113	A
Task 2 (combinatorial)	2.437	B *
Task 3 (probabilistic)	2.662	B *

The Tukey's test in Table 6 indicated that although there were significant differences among the three kinds of formal reasoning, the differences specifically analyzed between combinatorial and probabilistic were not significant. This gives support to the idea (Fischbein, 1975) that probabilistic reasoning may be dependent on combinatorial reasoning.

The Unit Test

The results for the five items of the unit test showed that 50.6% of the 150 students answered all of the items correctly. There was little difference in the sample of 71 students who were given the Piagetian interview tasks as 49.3% of them also answered all five items correctly. The most often missed question was the question on probability. Forty-nine students answered it incorrectly. The overall mean score for the 150 students was 3.79 while the 71 individuals had a mean score of 3.62. Tables 7 and 8 show the scores and results of the unit test viewed in categories of intellectual development (as determined by the Lawson Test) and broken down into proportional, combinatorial, and probabilistic reasoning for all 150 students.

It should be noted that since there was only one probabilistic reasoning question on the unit test that the means for that category would be expected to be much lower. Unit test results in the same categories for the 71 students given interview tasks are seen in Table 9.

TABLE 7

UNIT TEST SCORES

Test Items	Mean	S.D.
U1 Proportional reasoning	.84	.37
U2 Proportional reasoning	.69	.46
U3 Combinatorial reasoning	.89	.32
U4 Combinatorial reasoning	.71	.45
U5 Probabilistic reasoning	.65	.48

TABLE 8

UNIT TEST MEANS

(N=150)

	Concrete (N=23)	Transitional (N=83)	Formal (N=44)
Proportional	1.22	1.48	1.80
Combinatorial	1.30	1.54	1.89
Probabilistic	0.26	0.63	0.91
Overall	2.78	3.65	4.59

Table 9 also indicates that concrete and transitional students had the greatest difficulty with probability and proportions, but formal-operational students had almost the same degree of success on all three areas of reasoning.

For both the entire sample of 150 and the sample of 71 there was significantly more success on the unit test for

TABLE 9

UNIT TEST MEANS

(N=71)

	Concrete (N=28)	Transitional (N=27)	Formal (N=16)
Proportional	1.07	1.48	1.88
Combinatorial	1.36	1.56	1.88
Probabilistic	0.43	0.74	0.94
Overall	2.86	3.78	4.69

those students who were at a higher stage of intellectual development. In all categories the mean scores of transitional students were higher than those of concrete students, and the mean scores of formal thinkers were higher than both concrete and transitional. Intellectual levels for the 71 were determined by the Piagetian interviews.

Figure 2 illustrates the scores of the 71 students on the unit test.

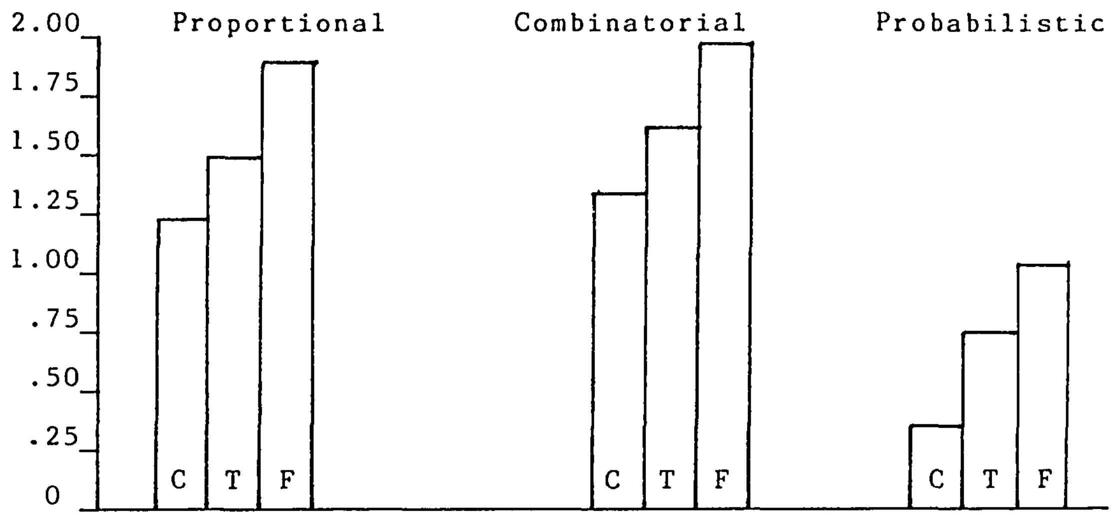
The Post-Test

The six items on the post-test were divided evenly into the three categories of proportional, combinatorial, and probabilistic reasoning. Of the 150 students who took the post-test, only twelve (8%) answered all of the items correctly. Fifteen students answered all six items incorrectly, and fifteen were able to answer only the first two items (Proportional reasoning) correctly. Of the 71 students

FIGURE 2

GROUP MEANS FOR UNIT TEST

(N=71)



Note. The values for probabilistic means represent one half the number of questions seen in the other two sets of columns.

who were given the Piagetian tasks, only four (5.5%) answered all correctly; and nine answered none correctly. Again there were a large number who could answer only the proportional reasoning items satisfactorily as 10 of the 71 fell in this category. The overall mean score for the 150 students was 2.82 while the overall mean for the sample of 71 was 2.52. Table 10 shows the scores of the post-test, and Table 11 shows the group means for the 150 students who took the post-test. Their intellectual levels are derived from their Lawson Test scores.

The 71 students (of the 150) who were given interview tasks also performed more poorly on the post-test than they had on the unit test. Table 12 shows their group means. The intellectual levels were determined by the Piagetian interview tasks.

TABLE 10

POST-TEST SCORES

Test Item	Mean	S.D.
P1 Proportional reasoning	.73	.45
P2 Proportional reasoning	.60	.49
P3 Combinatorial reasoning	.36	.48
P4 Combinatorial reasoning	.58	.50
P5 Probabilistic reasoning	.16	.37
P6 Probabilistic reasoning	.43	.50

TABLE 11

POST-TEST MEANS

(N=150)

	Concrete	Transitional	Formal
Proportional	0.91	1.18	1.77
Combinatorial	0.35	0.81	1.45
Probabilistic	0.22	0.43	1.05
Overall	1.48	2.42	4.27

Comparisons Of Results

Pearson correlations for the unit test, post-test, and

TABLE 12

POST-TEST MEANS

(N=71)

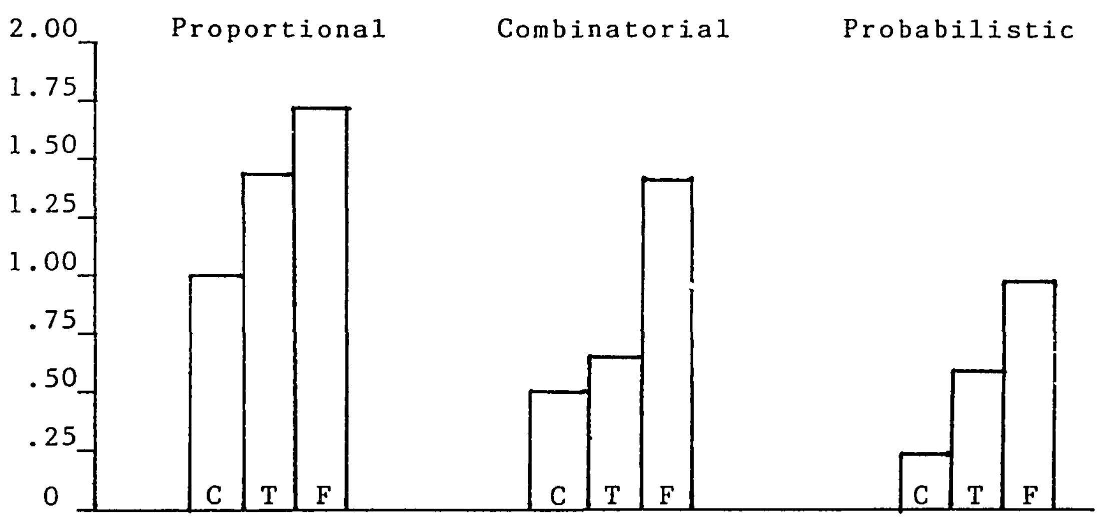
	Concrete	Transitional	Formal
Proportional	0.93	1.44	1.69
Combinatorial	0.43	0.59	1.38
Probabilistic	0.25	0.56	0.94
Overall	1.61	2.59	4.00

The results shown in Table 12 are illustrated in Figure 3.

FIGURE 3

GROUP MEANS FOR POST-TEST

(N=71)



Lawson Test were sought to show significant relationships among those various elements. Correlations for the means of all 150 students are shown in categories according to type of problem (proportional, combinatorial, and probabilistic) and according to overall score (Table 13).

TABLE 13

PEARSON CORRELATIONS OF MEANS

(N=150)

	Proportional	Combinatorial	Probabilistic	Overall
Unit test/ post-test	.37	.35	.53	.58
Unit test/ Lawson Test	.14	.31	.35	.46
Post-test/ Lawson Test	.23	.44	.33	.59

For the sample of 71 students from among the 150, the Pearson correlations are seen in similar categories in Table 14. This also includes the comparison with interview tasks since these students had all completed the tasks.

The Pearson correlation values in Table 14 indicate that there is a lower correlation between the unit test and each of the measures of intellectual level (the Lawson Test and the interview tasks) than is seen between any other two instruments. If success on the unit test is dependent on short-term memory, then this low correlation is no surprise. Although none of the correlations is extremely high, the overall scores correlate more highly on almost all comparisons than they do on any individual reasoning type.

Good and Fletcher (1981) pointed out the importance of

TABLE 14

PEARSON CORRELATIONS OF MEANS

(N=71)

	Proportional	Combinatorial	Probabilistic	Overall
Unit test/ post-test	.52	.34	.48	.59
Unit test/ interview tasks	.33	.30	.47	.45
Unit test/ Lawson Test	.23	.37	.33	.55
Post-test/ interview tasks	.33	.33	.49	.55
Post-test/ Lawson Test	.33	.40	.31	.65

reporting explained variance or magnitude of effects. They indicated that reporting the statistic r^2 estimates the proportion of variance in score Y that can be attributed to variance in score X. Squaring the correlational analysis values in Table 14 would show that the actual variance accounted for would range from 5% (for a value of .23) up to 42% (for a value of .65). According to this analysis, the Pearson correlation value of .23 would be obviously weak although at the .05 level a Student's _t_ test would indicate its acceptability.

Pearson correlations of interview tasks with reasoning types (Tables 15 and 16) indicated that values were higher in the overall comparisons than in any category-by-category comparison. Table 16 also illustrated that correlations between different reasoning types were often higher than for corresponding reasoning types. For example, the correlation between probabilistic means on the tasks with the combinatorial means on the post-test was .42, while the correlation between proportional items was only .32.

TABLE 15

PEARSON CORRELATIONS FOR INTERVIEW TASKS AND POST-TEST

(By Intellectual Levels And Reasoning Types)

ITEMS	Total (N=71)	Concrete (N=28)	Transitional (N=27)	Formal (N=16)
Tasks/Post-test (proportional)	.33	.08	.06	.19
Tasks/Post-test (combinatorial)	.33	.18	.07	.67
Tasks/Post-test (probabilistic)	.49	.00	.12	.55
Tasks/Post-test (overall)	.55	.25	.25	.54

In view of the hypotheses proposed for this study, the two most important instruments were the Piagetian interviews and the post-test. A factor analysis (Table 17) was run on the scores of the 71 subjects on those two instruments to see if the three factors of proportional, combinatorial, and probabilistic reasoning would be separated.

The analysis in Table 17 did not break ideally into three separate categories, and the loading of the three types

TABLE 16

PEARSON CORRELATIONS OF INTERVIEW TASKS AND POST-TEST ITEMS

(By Reasoning Types)

	TASKS			POST-TEST		
	Prop.	Comb.	Prob.	Prop.	Comb.	Prob.
Tasks (Proportional)	1.00	.55	.39	.32	.45	.28
Tasks (Combinatorial)	.55	1.00	.33	.33	.34	.38
Tasks (Probabilistic)	.39	.33	1.00	.35	.42	.47
Post-Test (Proportional)	.32	.33	.35	1.00	.35	.28
Post-Test (Combinatorial)	.45	.34	.42	.35	1.00	.51
Post-Test (Probabilistic)	.28	.38	.47	.28	.51	1.00

of reasoning did not fit well into the two factors that were separated. Valid items were considered to be those which loaded as high as .50 on one factor without a loading as high as .40 on the other (Kim & Mueller, 1978). Factor 1 loaded with P5 (probabilistic) and all three task itemsssss while Factor 2 loaded with P6 (probabilistic) and P1 and P2 (both dealing with proportional reasoning).

Factor analysis of post-test and tasks lent no confirmation to the hypothesis that the three types of reasoning under consideration are clearly distinct. It may be that the two factors suggested by the analysis relate more directly to

TABLE 17

FACTOR ANALYSIS OF POST-TEST ITEMS AND INTERVIEW TASK ITEMS

(Varimax Rotated Factor Structure)

Item	Factor 1	Factor 2
P1 (proportional)	0.06391	0.70739
P2 (proportional)	0.22569	0.66899
P3 (combinatorial)	0.37104	0.47373
P4 (combinatorial)	0.31249	0.44073
P5 (probabilistic)	0.65148	0.21639
P6 (probabilistic)	0.09179	0.71335
T1 (proportional)	0.86548	0.13845
T2 (combinatorial)	0.83804	0.14879
T3 (probabilistic)	0.83429	0.24985

Variance explained by each factor.

Factor 1 = 2.870606 (10%)

Factor 2 = 2.026030 (5%)

intellectual levels since all three task items and one of the most difficult post-test questions were loaded with the same factor.

The comparisons of the three reasoning types with the three intellectual levels require a repeated measures nested design for analysis of variance. Tables 18-21 show treatment of the results of levels determined by the Lawson Test with both the unit test and post-test and the levels determined by the Piagetian interview tasks with both tests.

TABLE 18

ANALYSIS OF VARIANCE INTELLECTUAL LEVELS VS. REASONING TYPES

(From Lawson Test And Unit Test)

Source of Variance	DF	Sum of Squares	F	P
Intellectual Levels	2	114.391	3.72	.0001
Reasoning Type	2	83.751	203.07	.0001
Level X Type	4	.288	.35	.845

TABLE 19

ANALYSIS OF VARIANCE INTELLECTUAL LEVELS VS. REASONING TYPES

(From Lawson Test And Post-Test)

Source of Variance	DF	Sum of Squares	F	P
Intellectual Level	2	152.020	2.80	.0001
Reasoning Type	2	40.373	55.48	.0001
Level X Type	4	.652	.45	.774

TABLE 20

ANALYSIS OF VARIANCE INTELLECTUAL LEVELS VS. REASONING TYPES

(From Interview Tasks And Unit Test)

Source of Variance	DF	Sum of Squares	F	P
Intellectual Level	2	12.273	8.02	.0007
Reasoning Type	2	30.428	87.83	.0001
Level X Type	4	0.825	1.19	.3176

POST HOC ANALYSIS OF REASONING TYPES

TUKEY'S STUDENTIZED RANGE TEST

(Means with same letter not significantly different)

Item	Mean	Tukey Grouping
U1 & U2 (proportional)	1.409	A *
U3 & U4 (combinatorial)	1.535	A *
U5 (probabilistic)	0.662	B

POST HOC ANALYSIS OF INTELLECTUAL LEVELS

(Levels with same letter not significantly different)

Intellectual Level	Least Square Means	Tukey Grouping
Concrete-operational	0.925	A
Transitional	1.275	B
Formal-operational	1.555	C

The post hoc analysis indicated that although there were significant differences among the three types of test items there was not a significant difference between proportional reasoning questions and combinatorial reasoning questions. The unit test questions did not discriminate as well among the three reasoning types as did the post-test. Students' efforts to memorize the problem solving techniques did not appear to last over the eight-week interim between the two tests.

Each ANOVA done on the comparison of different test

TABLE 21

ANALYSIS OF VARIANCE INTELLECTUAL LEVELS VS. REASONING TYPES

(From Interview Tasks And Post-Test)

Source of Variance	DF	Sum of Squares	F	P
Intellectual Level	2	17.905	12.86	.0001
Reasoning Type	2	20.501	29.84	.0001
Level X Type	4	1.346	0.97	.4248

POST HOC ANALYSIS OF REASONING TYPES

TUKEY'S STUDENTIZED RANGE TEST

(Means with same letter not significantly different)

Item	Mean	Tukey Grouping
P1 & P2 (proportional)	1.2958	A
P3 & P4 (combinatorial)	0.7042	B
P5 & P6 (probabilistic)	0.5211	C

POST HOC ANALYSIS OF INTELLECTUAL LEVELS

(Levels with same letter not significantly different)

Intellectual Level	Least Square Means	Tukey Grouping
Concrete-operational	0.531	A
Transitional	0.885	B
Formal-operational	1.311	C

instruments showed significant main effects. The three intellectual levels were significantly different in each case. That is, on both the unit test and post-test there was graduated success from the concrete-operational level to the transitional level to the formal-operational level. The other main effect, that of the three different reasoning types, also showed significant differences. The comparison of level by reasoning type showed no significant interaction in any of the four ANOVAs. Both measures of intellectual development, the Lawson Test and the interview tasks, gave the same significant main effects.

CHAPTER V

CONCLUSIONS AND DISCUSSION

This study was designed to examine the reasons that students have difficulty in solving problems in the area of simple Mendelian genetics. The specific theoretical basis for the investigation was Piagetian stage development, with the premise being that genetics problems require formal-operational intellectual abilities for their successful completion and full comprehension. The areas of formal thought that were chosen for analysis were proportional, combinatorial, and probabilistic reasoning. These three intellectual processes are seen in genetics problems that require ratios to be identified from a Punnett square, combinations of gametes from a given genotype to be listed, and probability of gamete formations or zygote combinations to be estimated.

A large sample of students (150) was given a group Piagetian test, a unit test (following lecture/discussion instruction in genetics), and a post-test (retention test) eight weeks later. A sample of 71 students from the group was also given Piagetian interview tasks over the areas of proportional, combinatorial, and probabilistic reasoning. The resulting data from these four instruments were analyzed for relationships to the hypotheses that formal thought, in general, and the specific three areas of formal thought, in particular, are directly related to successful understanding of Mendelian genetics.

Summary of Results

Analysis of the results from the four instruments used in this study and reported in Chapter IV leads to the following conclusion:

1. The use of the Lawson Test indicated that the sample of 71 who were later given Piagetian interview tasks were representative subjects. The students in the interview group were within the normal range of performances for both the unit test and the post-test. The Lawson Test results had slightly higher overall correlations with both the unit test and post-test than did the results from the interview task students.
2. Although the unit test problems required the students to work through an entire genetics problem with success on some parts dependent on success on earlier parts of a problem, the results were still significantly higher on the unit test than on the post-test. Correlations of the unit test with the intellectual levels indicated the unit test was not

related to the levels of intellectual development.

3. The results of the post-test indicated a significant drop in the students' abilities to solve genetics problems. The factor of forgotten definitions of terms used in the problems should have been adequately compensated for by the vocabulary list provided during the administration of the test. However, the motivational factor of course grade improvement was not a consideration for the post-test since no grade credit was promised for that exercise. The correct conclusion may be that the students never fully understood the problems when they took the unit test but were able to become familiar enough with the process of building a Punnett square to do well on the initial test. Enough time had elapsed that memorization of classic ratios and the number of gametes that are produced by heterozygotes would not likely have allowed students to perform successfully on the post-test.

4. The outstanding feature of the post-test results was the clear superiority of students of higher Piagetian intellectual levels. Not only did they score higher overall, but they performed with greater success on problems related to each of the areas of proportional, combinatorial, and probabilistic reasoning.

5. Results on genetics problems that called for combinatorial reasoning and probabilistic reasoning were respectively lower than problems calling for proportional reasoning. These results were inconsistent with the scores on the Piagetian interview tasks that were lower in the proportional reasoning area.
6. Pearson correlations of means within the specific categories of proportional, combinatorial, and probabilistic thought were not consistently high and in general accounted for little of the variance. Most overall correlations accounted for a higher percentage of the variance.
7. Analysis of variance results (Tables 18-21) indicated significant differences among the concrete-operational, transitional, and formal-operational students on the three categories of thought (proportional, combinatorial, and probabilistic) on both the unit and post-test results.
8. The factor analysis (Table 17) did not indicate a clear-cut separation for the task items and reasoning type post-test items. If all items measured the reasoning type intended, then items from both instruments would have been separated into three factors according to reasoning type. The two factors that were identified may have been simply a

division based on level of intellectual development or difficulty of questions. Regardless, no strong evidence was indicative of a correspondence between task items and post-test items that attempted to measure the same reasoning types.

Discussion

At this point the question needs to be asked, "How do these results support the hypotheses proposed?" The first three hypotheses stated in the first chapter of this study indicated that there would be a strong relationship between aspects of formal thought and success in solving genetics problems that call on these formal thought processes:

1. There will be a strong relationship between a student's ability to use combinatorial reasoning and his understanding of Mendel's Law of Independent Assortment as it relates to possible gamete combinations.
2. There will be a strong relationship between a student's ability to use proportional reasoning and his ability to understand ratios of offspring as seen in a Punnett square.
3. There will be a strong relationship between a student's ability to use probabilistic logic and his understanding of chances of possible gamete and zygote formations.

The results seen in this study do not support these three hypotheses. Specific identification of areas of formal thought related to corresponding areas in genetics were not conclusively shown by any of the statistical measures used. For example, the Pearson correlations (Table 14) for the interview tasks on proportions, combinations, and probability with corresponding items of the post-test had values of .33, .33, and .49, respectively. These values are not high and do not account for a high percentage of the variance. Table 15 indicated that correlations considered within the three separate intellectual levels are extremely low. Interview tasks and post-test items should provide the most direct measure of the first three hypotheses. However, correlations for the interview tasks with the post-test items in proportional reasoning were .08. .06, and .19 for the concrete, transitional, and formal students, respectively. Table 16 indicates that correlations are often higher between different reasoning types than between similar types. For instance, combinatorial/proportional on the interview tasks and post-test had a correlation of .44 while proportional/proportional correlated at .32. Also, combinatorial/probabilistic correlated at .42 compared to .34 for combinatorial/combinatorial. Overall correlations, i.e., correlations representing combined reasoning types, were consistently higher. Again, this indicates a lack of direct correspondence between specific formal reasoning skills and similar areas in genetics problems since overall correlations are higher than the individually considered factors.

The factor analysis of interview tasks and post-test items (Table 17) also failed to support the hypotheses that specific formal reasoning types could be related directly to genetics problems. Since all three interview tasks loaded together, it is more likely that intellectual levels were being factored out rather than specific reasoning skills. As was proposed in the summary, the individual task items would have needed to load with some corresponding post-test items to have been convincing evidence for correspondence of reasoning skills; and such was not the case.

The third area of statistical treatment that failed to support the first three hypotheses of this study was the use of ANOVAs. Analysis of variance for the intellectual levels with both the unit test and the post-test (Tables 20 & 21) indicated significant main effects for reasoning types and intellectual development but no interaction effects. Post hoc analysis of reasoning types for the interview tasks (Table 6) showed proportional reasoning to be more difficult than combinatorial or probabilistic reasoning. If there were truly correspondence between specific Piagetian tasks and reasoning types, then the same pattern could be expected for the post hoc analysis of ANOVAs for the interview tasks with both the unit test and post-test. Tables 20 and 21 do not, however, show this pattern. In both cases proportional reasoning is less difficult than combinatorial, with probabilistic being most difficult. This, coupled with the other findings, makes a case for the rejection of hypotheses concerned with direct relationships among the reasoning types and their Piagetian measurement.

The fourth hypothesis proposed in Chapter I was, "Students who score well on Piagetian tasks will show stronger retention of genetics problem-solving in a post-test." This hypothesis was well supported by the mean scores of students on interview tasks and the post-test. Table 21 indicated significant main effects for both the intellectual levels and reasoning types from the interview tasks and post-test scores. Other results presented in Chapter IV give strong support to the claim that students need to have developed their intellectual capacities to the formal-operational level to successfully learn Mendelian genetics. In each consideration post hoc analysis of the ANOVA results (Tables 20 and 21) indicated significantly higher unit test or post-test mean scores for the students with higher scores on the Piagetian measures of intellectual ability. Piagetian levels determined by performance on the interview tasks always met with the same results, i.e., the higher the intellectual level of the student, the better his score on each of the reasoning types presented in the genetics problems.

In considering the results related to the first four hypotheses of this study, one strong general conclusion emerges: we can say with a high degree of certainty that formal thought is necessary for solving Mendelian genetics problems, but we do not know enough about formal-operational thought to relate its characteristics directly to what we perceive to be the specific reasoning type necessary in solving genetics problems. This conclusion should serve as a warning that a student's success on a specific Piagetian task used to assess his intellectual level does not assure his success in curriculum content that is assumed to require the same specific reasoning type.

The last hypothesis proposed in Chapter I indicated that this study might show a hierarchical relationship among proportional, combinatorial, and probabilistic reasoning. The poor results on proportional interview tasks coupled with higher success on the post-test proportional questions leaves the question of hierarchical relationships largely unresolved. If the unit test and post-test items can be accepted as good measures of the three reasoning types, then the consistently higher scores in proportional problems, with probability problems always showing the highest difficulty, indicate a needed area of attention in genetics instruction. Regardless of the intellectual level of the student, the order of greatest difficulty for problem solving appears to be probability, then combinatorial reasoning followed by proportional reasoning. It appears that few problems used in genetics instruction call for probability reasoning without requiring that a student first be able to work out a combinatorial relationship.

Implications Of This Study

The most obvious implication seen in the results of this study is the need to identify appropriate content for instruction based on intellectual development of students. Genetics is an extremely valuable domain of study within biology, but great care should be taken to assure that when genetics problems are included in the curriculum the students are capable of doing what they are asked to do. Presentation of formal concepts seen in Mendelian problems to students who are concrete-operational will most certainly result in frustration. This would imply that Mendelian genetics has little place in the middle-school or high school classroom where a high percentage of students are non-formal. The impossibility of presenting the formal concepts of genetics as concrete instruction should show the inappropriateness of this study for many science classrooms (Schneider & Renner, 1980). Those who teach introductory courses in biology on the college level might insure greater success among students by making sure that genetics problems are studied as late in the course as possible, allowing transitional students more time and experience. Use of group tests of intellectual development would be useful to alert teachers to their students' potential difficulties. Since Mendelian genetics is one of the few areas of a college general biology course that lends itself readily to problem-solving, most teachers are reluctant to eliminate it from their courses. Perhaps the results of this and other studies can help them see the futility of such content for the non-formal student.

The use of the Punnett square as the teaching model for genetics problems is a major obstacle to those students who do not operate in the formal realm. The model is of necessity a model of proportions and probabilities; and in order to build the grid, a student must be able to identify the combinations of gametes that can be produced by parent organisms. Although the Punnett square may be a clear representative model in the eyes of the instructor and perhaps in the eyes of the more intellectually advanced students, the implication of this study is that it is too advanced a model for a large portion of the students.

A major consideration should be the enhancement of opportunities for students in the transitional and early stages of formal thought to develop proportional, combinatorial, and probabilistic reasoning powers. Although this study did not show a direct correspondence of these reasoning abilities with genetics problems, those students who could function in those areas were the most successful. If content demands these intellectual abilities, then it is incumbent upon teachers to know that the intellectual skills of their students are advanced to a level enabling them to deal with such content. Again, this calls for testing of students' intellectual levels.

Suggestions For Further Research

A successful identification of the aspects of formal thought inherent in genetics problem solving would add to the ability to organize instruction and curriculum content. In addition to the areas of proportional, combinatorial, and probabilistic reasoning examined in this study, propositional logic may be a fruitful realm of consideration.

Since the Punnett square is a model with formal aspects, it may be that optional methods of problem presentation could prove to be more successful with non-formal students. Comparisons of success with other methods of problem presentation analyzed by intellectual level might lend valuable input toward the best method of genetics instruction. However, the underlying principles of Mendelian problems are formal regardless of the technique used to present the crosses.

Movement into formal thought by students who experience instruction in permutations and probability in introductory college mathmatics courses might correspond well to success in genetics problem solving. Implications of such relationships might prove useful in identifying the best sequencing of science courses.

There are aspects of genetics that may not lean as heavily on formal thought as do Mendelian problems. Concrete-operational students may be able to work well with certain basic descriptive relationships within the realm of human genetics, and attention should be given the development of concepts that are appropriate for instruction at that level. Such instruction could lay a strong foundation for later concepts rather than cause frustration that destroys student interest altogether.

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APPENDIX A

Genetics Unit Objectives

At the conclusion of this unit, students should be able to

1. Relate the meiotic process to gamete formation
2. Use the Punnett square to solve problems involving the Law of Dominance, the Law of Independent Assortment, and the Law of Segregation
3. Identify how many possible gametes could be produced by an individual of a given genotype
4. Identify both genotype and phenotype ratios of offspring from a Punnett square
5. Predict the chances for a gamete to be formed from a given genotype
6. Predict the chances of a zygote of a certain genotype being produced by given parent organisms
7. Identify reasons why garden peas were such an ideal experimental organism for Mendel
8. Identify the genotypes of parent organisms having been given the genotypes of their offspring
9. Define or identify the following terms: dominant, recessive, hybrid, homozygous, heterozygous, gamete,

allele, zygote, phenotype, genotype, segregation, independent assortment, f_1 generation, f_2 generation

APPENDIX B

Genetics Problems

(Rahn, 1980, pp. 569, 570)

In guinea pigs black coat color (B) is dominant to white (b). Use this information to answer the next questions.

1. If a homozygous black guinea pig mates with a homozygous white guinea pig, what will be the phenotype of the F_1 generation? Of the F_2 generation? Be sure to indicate ratios.
2. A black guinea pig mates with a white one. If they have a large number of offspring and all are black, what is the most likely genotype of the black parent? If half of the offspring had been black and half white, what would you conclude about the genotype of the black parent? Could all the offspring have been white? Why or why not?
3. Can you determine the genotypes of all the individuals in the following family tree?

```
White X black
    black X white
        black X black
            white
```

4. In guinea pigs short hair is dominant to long hair. If a homozygous black short-haired guinea pig mates with a white long-haired guinea pig, what will be the phenotype of the F_1 generation? Of the F_2 generation? Be sure to indicate ratios.

5. Indicate the most likely genotypes of the parents in the following crosses.

   a. black short hair X white long hair
      all black short hair

   b. black short hair X white long hair
      ½ black short hair
      ½ black long hair

   c. black short hair X white long hair
      ½ black short hair
      ½ white short hair

   d. black short hair X white long hair
      ¼ black short hair
      ¼ black long hair
      ¼ white short hair
      ¼ white long hair

6. Show a Punnett square for a cross between two guinea pigs that are heterozygous for color and hair length. State the phenotype and genotype ratios of the offspring.

7. What are the chances that an offspring of the cross in problem #6 would show only recessive traits?

APPENDIX C

<u>Genetics Unit Lecture Schedule</u>

Day One:
1. Review of mitosis and meiosis with special emphasis to the reduction of chromosome number in gamete production
2. Historical background of Mendel's experiments

Day Two:
1. Reasons for Mendel's ease of experimentation with garden peas
2. Introduction of the Law of Dominance, with examples
3. Introduction of the Punnett square model for illustrating problems

Day Three:
1. Introduction of the Law of Segregation and the Law of Independent Assortment
2. Practice examples of gamete numbers formed from different gene combinations
3. Use of 2^N to calculate number of gametes possible

Day Four:
1. Examples of probabilities of gamete formations and offspring combinations from Punnett squares
2. Use of test crosses or back crosses to identi-

fy the genotypes of parent organisms

3. Classic monohybrid cross and dihybrid cross using Mendel's garden pea example

4. Assignment of homework problems

Day Five: 1. Use of homework problems to pick genotype and phenotype ratios from Punnett squares

Day Six: 1. Completion of homework problems review

2. Sample problems for codominance and incomplete dominance

Day Seven: 1. Use of dihybrid cross Punnett square to pick out ratios and probabilities of offspring

Day Eight: 1. Sample problems were given as a test preparation

2. Review of gamete combinations from given genotypes and classic ratios seen in off-spring

Day Nine: 1. Short review and question-answer session

2. Administration of unit test

APPENDIX D

Unit Test Problems

1. In garden peas, tall (T) is dominant over short (t). Illustrate, with a Punnett square, a cross between two heterozygous tall pea plants and state the genotype ratio.
2. In some rabbits, long hair (L) is dominant over short hair (l); and brown color (B) is dominant over white (b). Cross a rabbit that is heterozygous for both traits with one that is short-haired and heterozygous brown. Show a Punnett square for the cross and state both the phenotype ratio and the probability that an offspring will have only recessive genes.

APPENDIX E

Genetics Vocabulary

1. chromosomes--rod-shaped bodies found in cell nuclei. They possess the genes.
2. dominant--a genetic trait that covers up or "masks" a recessive trait and won't let the recessive trait be shown.
3. gamete--a sex cell, such as an egg or a sperm.
4. gene--a unit of heredity found in the chromosomes.
5. genotype--the genetic make-up of an individual, i.e. the genes for a trait that it possesses.
6. heterozygous--a term that describes genetic make-up in which the genes for a trait are different. (e.g. Aa)
7. homozygous--a term that describes genetic make-up in which both genes for a trait are alike. (e.g. AA or aa)
8. Law of Independent Assortment--During meiosis chromosomes are assorted randomly into the gametes.
9. meiosis--division that forms sex cells--chromosome number is reduced to half.
10. phenotype--the appearance of an individual.
11. Punnett square--a grid that shows gamete types on the

outside and zygote types within the boxes.

12. recessive--a genetic trait that will not show up in the presence of a dominant trait.