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ABSTRACT

An integral part of the curriculum in introductory biology courses is the study of Mendelian genetics. Results from genetics learning studies and needs assessments demonstrated the need for additional intensive research in biology education and genetics learning. There exists a lack of detailed information describing reasoning patterns and processes of learners solving genetics problems using an interactive medium to explore their ideas and test hypotheses. The purposes of this study were to: (1) explore problem solving behaviors and genetics concepts employed by experts and novices during interaction with a genetics computer simulation; and (2) examine, extract, and analyze common and unique characteristics of successful and unsuccessful subjects. Three experts (Ph.D.s in Biology) and ten novices (advanced biology secondary students) participated in the study. Two experts and two novices exhibited the most complex patterns of problem-solving sequences and principally used problem-solving sequences. These were the successful subjects. The least successful subjects, five novices, exhibited more random approaches during problem solving. An intermediate group of less successful problem solvers exhibited some of the problem solving sequences of successful subjects. Included are tables, diagrams, and a list of references. (RT)

PROBLEM SOLVING BEHAVIORS OF SUCCESSFUL AND UNSUCCESSFUL SUBJECTS LEADING TO A GENETICS PROBLEM SOLVING MODEL

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ABSTRACT

The study of Mendelian genetics is an integral part of the curriculum in introductory biology courses at secondary and post-secondary levels. Results from previous genetics learning studies and needs assessments demonstrated the need for more intensive research in biology education in general and genetics learning in particular. Problem solving behaviors and genetics concepts employed by experts and novices during interaction with a genetics computer simulation, Catlab (Kinnear, 1982), were explored. Thirteen subjects investigated a common hypothesis on a specific genetic trait (coat patterns).

Successful subjects (two experts and two novices) exhibited the most complex patterns of problem solving sequences and used principally description problem solving sequences. The least successful subjects (five novices) exhibited more random approaches during problem solving that did other subjects. An intermediate group of less successful problem solvers (one expert and three novices) exhibited some of the problem solving sequences of successful subjects.

Successful problem solving in genetics appeared to include the use of description problem solving sequences and the use of specific genetics concepts. Verbalizing description problem solving sequences may have helped subjects in recognizing, analyzing, interpreting, and evaluating underlying patterns characteristic of inherited traits. The findings reported in this study may reflect situations where successful problem solvers can utilize a variety of approaches (pathways) and draw upon support structures of quantitative or qualitative problem solving sequences and general or specific genetics concepts to investigate hypotheses. A performance-based model for genetics problem solving was formulated from conclusions from this study. The proposed model represented an attempt to integrate problem solving behavior sequences with the use of genetics concepts to examine and to predict successful or unsuccessful performances.

Further research is nneded to elucidate the linkages and levels of variables influencing successful problem solving. Analyses of descriptive research studies, such as the one described here, can serve as important sources of information about cognitive and affective behaviors and computer-based education. Such studies can aid our understanding of how learners develop important scientific concepts and problem solving skills and strategies. In addition, these studies provide information for teachers to employ appropriate instructional strategies based on learning models.

PROBLEM SOLVING BEHAVIORS OF SUCCESSFUL AND UNSUCESSFUL SUBJECTS LEADING TO A GENETICS PROBLEM SOLVING MODEL

Introduction

The study of Mendelian genetics is an integral part of the curriculum in introductory biology courses at secondary and post-secondary levels. Results from previous genetics learning studies and needs assessments (Hildebrand, 1985; Scriver, Scriver, Clow, and Schok, 1978) demonstrated the need for more intensive research in biol: gy education in general and genetics learning in particular. Research studies in genetics have examined how students use procedural and conceptual knowledge to solve problems (Stewart, 1982; Stewart, 1985; Smith and Good, 1984; Walker, Hendrix, and Mertens, 1980; and Stewart and Van Kirk, 1981). There exists, however, a lack of detailed information describing reasoning patterns and processes of learners solving genetics problems using a more interactive medium through which to explore their ideas and test hypotheses.

Purpose of the Study

Problem solving behaviors and genetics concepts employed by experts and novices during interaction with a genetics computer simulation, Catlab (Kinnear, 1982), were explored. The principal objective of this study was to examine, extract, and analyze common and unique characteristics of successful and unsuccessful subjects. The conclusions from the study were extended to a genetics problem solving model explaining performance levels of subjects.

Naturalistic Research Methodology

An intensive examination of learners' problem solving behaviors and genetics concepts during problem solving was conducted. A progression of research studies helped to focus and sharpen the research methodology and questions (Simmons, 1987). Each pilot study evolved in response to the need for understanding and elucidating the nature of genetics problem solving during an interactive learning session. The preliminary studies provided the heuristics for the research design of the main study. The naturalistic research methodology employed in the study reported here generated numerous questions requiring further research about learners' cognitive processes and needs. The collection of data from subjects' investigations and the extraction of patterns of behaviors and concept use resulted in the formulation of organizing schemes for data analysis. This is consistent with the purpose of naturalistic research (Easley, 1983). From these organizing schemes, more general patterns of problem solving behaviors were extracted to aid in analyzing data and coalescing signals and patterns of unique or common characteristics (Figure 1 and Table 2).

Naturalistic research studies entail the use of field methods such as case studies, clinical interviews, analysis of documents, and unstructured observations (Easley, 1983; Smith, 1982). Verbal protocols can also supply the data to which connections to performance models of problem solving can be inferred. Larkin and Rainard (1986) described one possible sequence of model building based on verbal reports:

1. collect a set of condition-action rules;
2. code the protocol statement to the corresponding action;
3. verify the protocol statements to the actions and conditions.

Verbal protocols can provide rich sources of data on cognitive processes and enhance the data base contributing to a more comprehensive understanding and description of cognition (Anderson, 1986).

Structured Observations

The field method employed in this study is termed "structured observation" (Krajcik, Simmons, and Lunetta, 1988). The use of this method facilitated the generation of data by the subjects during a "think aloud" protocol. From these data, patterns of behaviors and strategies were extracted for comparisons between individuals and between the groups of novices and experts. The subjects' performances on pretests and posttests of genetics concepts and genetics problems supplied additional data for analysis. These paper and pencil measures supplemented and corroborated the inferences drawn from analyses of their verbal protocols.

Videotape recordings of subjects' interactions with CATLAB were the primary source for verbal protocols for this investigation . An Apple IIe microcomputer was connected to the video input of a videocassette recorder (VCR). The audio input from subjects' verbalizations was filtered and amplified before recorded on videotape. This technique permitted the simultaneous recording of subjects' comments about their perceptions, observations, predictions, and explanations with the video display from the computer monitor. Videotape recordings were made duringeach subject's entire interaction with CATLAB.

All subjects received a briefing about the equipment and the expectations for their performance during the treatment. Subjects were specifically instructed to speak aloud during interaction with the program, with directions to give a running commentary on their perceptions, predictions, and actions and to share their thoughts even if they thought them to be insignificant . To acquaint subjects with the program menu and options, the investigator demonstrated how to generate parent cats, produce offspring, and pointed out features of the program (such as the numbering system used to identify cats). In addition, each subject received paper and pencil with strong encouragement to record their observations.

Computer Simulation

A computer simulation, CATLAB, was selected as the vehicle with which to examine subjects' genetics concepts and problem solving behaviors and strategies as they interacted with a model of a genetic population. CATLAB (Kinnear, 1982) served as the interactive medium for studies of learners' problem solving behaviors, strategies, and concepts. The CATLAB simulation required learners to:

1. generate their own question(s);
2. apply scientific principles;
3. decide which parameters or variables to control;

4. gather, record, analyze, and interpret data they generated;

5. draw conclusions to support or reject hypotheses.

The selection of the simulation, CATLAB, was based upon several criteria. The open-ended nature of the program was conducive to an inquiry laboratory format. CATLAB was based upon a valid scientific model of a genetic population. The program represented exemplary software that was available for use.

Treatment

Thirteen subjects investigated a common genetic trait (orange tabby striping) in cats. Three experts (PhD in Biology) and ten novices (advanced biology secondary students) participated in the study. Using a think aloud protocol (Ericsson and Simon, 1985; Krajcik, Simmons, and Lunetta, 1988), each subject's verbal commentaries and interaction with the simulation were recorded. A learning cycle organizer served as the framework for the computer instructional treatment. Subjects' behaviors and performances in an instructional environment based on the learning cycle were sampled. The learning cycle teaching model of exploration - invention -expansion (Renner, Abraham, and Birnie, 1986) was selected as the organizing framework for the CATLAB activity. Subjects were provided with opportunities to investigate genetic traits in cats by generating hypotheses, deciding what data to generate, collect, and interpret, and drawing conclusions about their hypotheses. In the exploration phase, subjects interacted with the program by experiencing information and concepts before conceptual organizers were discussed, by collecting data, and by searching for underlying patterns. The invention phase was marked by a discussion between the researcher and each subject on the actions and rationales the subject used to investigate the inheritance pattern of a specific trait. In the expansion phase, subjects solved problems by experimenting, redefining questions, investigating concepts, and relating concepts to new information.

Research Question

The performances of subjects investigating one specific genetic trait (a common hypothesis) during interaction with CATLAB were examined. The intersection of genetics concepts with problem solving behaviors and stratagies in a specific genetics context were also explored. The following general question was addressed: What problem solvin behaviors and strategies and genetics concepts do "novice" and "expert" subjects employ when investigating inheritance patterns with CATLAB?

Results and Conclusions

Patterns of the subjects' problem solving behaviors and verbalized genetics concepts were analyzed for common and unique charactersitcs. A scheme for categorizing genetics concepts was derived from the classification of physics concepts reported by Reif (1986). He defined two categories of physics concepts: entity concepts and property concepts. An entity concept denoted a particular or generic entity, such as the sun (particular) or a triangle (generic). A property concept was defined as a concept used to describe the functional relationships between other concepts. Based upon these definitions of concept categories, a key for entity and property concepts in genetics was constructed (Table 1). All genetics concepts verbalized by subjects were classified according to the dichotomous key.

The principal problem solving organizer employed in data analysis was modified from the Laboratory Strurcture and Task Analysis Inventory (Fuhrman, Lunetta, and Novick, 1982) and from the verbal protocol data generated by this study. A list of problem solving behaviors developed for use in coding subjects' behaviors is elaborated in Figure 2 and Table 2. The thirty-five categories of problem solving sequences were collapsed into four major categories of sequences: describing qualitative and quantitative observations, gathering data, concluding, and other sequences. Profiles of the problem solving behaviors over time were graphed for each subject (Figures 6, 7, and 8). From the profiles, the problem solving behaviors were collapsed into more generic problem solving sequneces represented in the flow charts in Figures 2, 3, and 4.

Three levels of problem solving performance were extracted from the data-successful, less successful, and least successful performance. Successful subjects (two experts and two novices) exhibited the most complex patterns of problem solving sequences and used principally description problem solving sequences (Figure 2, Tables 3 and 4). Most successful subjects verbalized a higher percentage of specific genetics concepts than general genetics concepts (Table 5). The least successful subjects (five novices) exhibited more random approaches during problem solving than did other subjects (Table 3 and Figure 4). Least successful subjects verbalized a higher percentage of general genetics concepts and described an array of alternative genetics concepts (Table 5). An intermediate group of less successful problem solvers (one expert and three novices) exhibited some of the problem solving sequences of successful subjects and verbalized a higher percentage of specific genetics concepts than general genetics concepts (Tables 3 and 5, Figure 3).

Successful subjects used primarily description sequences during all phases of problem solving (at the initiation, middle, and termination of hypothesis testing) (Figure 6). Describing observations and data may be an initial step in processing relevant information. According to Champagne, Gunstone, and Klopfer (1982) and White and Frederickson (1986), phycisists (experts) typically used a qualitative description approach prior to employing physics equations when solving a problem. This model of expert/novice problem solving may be applicable to the behaviors observed in successful and unsuccessful subjects in this study. For example, the behavior of Subject 3 (successful novice), who used qualitative description, was consistent with the behavior of the physicists during problem solving. This finding indicated that some common elements or characteristics appear to operate in genetics and physics problem solvers. The behavior of the other successful subjects who used principally quantitative sequences may reflect differences in the nature of the two science domains.

Most unsuccessful subjects used description problem solving sequences at the initiation of hypothesis testing (Figures 7 and 8). These subjects did not use description sequences during or at the termination of hypothesis testing. The least successful subjects used the smallest percentages of description sequences (Table 6). This indicated unsuccessful subjects may have bypassed a crucial step in successful problem solving. The omission or infrequent use of description problem solving sequences may result in learners overlooking signals or patterns within the data. By contrast, successful subjects continuously drew upon description sequences when analyzing and interpreting data. The occurrence of description problem solving sequences throughout hypothesis testing in successful subjects' investigations indicated that these sequences may be key elements contributing to successful performance. Descriptions of observations or data during analysis and interpretation may help in successful problem solving. The results from this study indicated that general strategies (such as description of observations) used as a principal problem approach may lead to successful performance.

Conclusion 1: Successful performance may have resulted from successful subjects' ability to select from and implement purposeful problem solving sequences.

This action may have led to more systematic data gathering and/or interpretation. The use of such sequences may have led subjects to attend to data cues characteristic of various inheritance traits. The altering patterns of problem solving sequences over time indicated that successful subjects employed and utilized those sequences (e.g. description) to generate relevant data, to interpret data correctly, and to determine which of their assumptions were supported by the data generated. The problem solving patterns of successful subjects suggested that they drew upon and used a greater variety of problem solving behaviors. Successful subjects may have a more developed sense of the strategic knowledge to employ during problem solving than unsuccessful subjects. However, some of the unsuccessful problem solvers (less successful subjects) possessed problem solving behaviors similar to the successful problem solvers. The organization and implementation of problem solving behavior patterns of unsuccessful subjects differed from the behavior patterns of the successful subjects. The unsuccessful subjects typically ordered or organized their problem solving behaviors in a more random manner than the successful problem solvers. In addition, the unsuccessful subjects employed segments of the description problem solving sequences which successful subjects employed.

Conclusion 2: Unsuccessful subjects used segments of the problem solving sequences used by successful subjects.

Unsuccessful problem solvers (one expert and eight novices) used parts of the entire problem solving sequences employed by successful problem solvers. This indicated that unsuccessful subjects neglected to use an important category of sequences during hypothesis testing. Unsuccessful subjects' selection of parts of the sequences employed by successful subjects may reflect a lack of:

1. an understanding of how to solve the problem
2. an appropriate interpretation or formulation of the problem statement
3. a useful or appropriate internal representation to guide the selection of a strategy
4. integration and implementation of sequences
5. discrimination between cues or patterns within the data.

Unsuccessful problem solvers may have an underdeveloped sense of purpose in selecting an appropriate strategy to use during hypothesis testing. These subjects may rely upon and employ insufficiently developed logical thinking skills, resulting in more random approaches toward problem solving. Unsuccessful subjects may nor have realized the consequences of their decisions or actions during problem solving. The unsuccessful subjects also used problem solving sequences containing problem solving behaviors in different orders from the sequences of successful subjects.

Conclusion 3: The majority of successful subjects verbalized a greater percentage of entity concepts than property concepts during hypothesis testing.

The higher percentage of entity concepts verbalized by successful subjects (one expert and two novices) indicated that these subjects were focussing on specific cues during data processing, searching for patterns within the data, and drawing upon specific concepts to aid in explanation of the data. This supports the idea that domain specific knowledge may be linked to successful problem solving. However, one expert's successful performance (employing general genetics concepts) indicated that verbalizing domain specific knowledge may contribute to successful problem solving. The finding that one successful subject (11) used a higher percentage of property concepts and a quantitative problem solving sequence to extract data patterns suggested that he drew upon general relationships of concepts to describe his observations., However, he used a quantitative strategy to uncover the exact relationship operating in the orange striping trait. This subject determined the inheritance characteristics by using mathematical ratios of expected and observed outcomes. His successful performance may have reflected compensation for using more general concepts with a quantitative problem solving approach. The verbalization of more general concepts in combination with the extraction of mathematical patterns from the data may have led to his successful performance.

Unsuccessful subjects' articulation of a higher percentage of the property class of concepts may have reflected the subjects' use of informal ("everyday") knowledge modes. Reif (1986) noted that novices used fragmentary knowledge or intuition and rarely translated a concept into a more formal definition . Novices also overlooked significant discriminations within concepts (Reif, 1986). He postulated this inability of novices to discriminate led to the generation of fragmentary knowledge, resulting in misconceptions.

The results reported here were consistent with Reif's generalizations about concept interpretation. If the assumption that the verbalization of a concept implies the interpretation of the concept by a subject is true, then the concepts verbalized by unsuccessful subjects may be explained by examining formal versus informal interpretation modes. For instance, the higher percentage of the property class of concepts may have reflected the fragmentary knowledge of unsuccessful subjects. If subjects used fragmentary knowledge during problem solving, then it may be reasonable to assume that the nature of that knowledge is more general rather than specific. Thus, unsuccessful subjects drew upon the more general concepts when solving problems. The finding that some of the less successful subjects used a higher percentage of entity concepts during problem solving may reflect a movement of subjects along a continuum from fragmentary (or informal) knowledge to integrated (or formal) knowledge interpretation. Four of the unsuccessful subjects focussed on entity concepts, four on property concepts, and one subject equally on both classes of concepts. This may have resulted in the subjects misinterpreting ideas on a large scale or overlooking more subtle or detailed cues.

Conclusion 4: Successful performance in problem solving involved the intersection of quantitative or qualitative description skills with the use of specific scientific concepts.

Successful problem solving may be a combination of the appropriate problem solving sequences (such as qualitative or quantitative description) and the verbalization or use of specific genetics concepts. The majority of successful problem solvers used quantitative description sequences to aid in extracting, analyzing and interpreting patterns within the data generated. Only one of the successful problem solvers did not rely upon quantitative description sequences as greatly as the other successful problem solvers. Instead, she (Subject 3) focussed upon qualitative description sequences during hypothesis testing and traced the transmission of genes through various kinds of crosses. The performances of the unsuccessful subjects indicated that these subjects lacked the domain specific knowledge to describe their observations or were not be able to discern characteristic signals of specific concepts or genetics principles within the data patterns.

The findings from this study suggested that subjects performed at differing levels of problem solving. The variety of approaches used by successful subjects (qualitative and quantitative description and conclusion sequences) suggested that human problem solving and information processing do not occur in the same manner as the computer processing analog proposed by Newell and Simon (1972). The evidence from this study strongly suggests that problem solving within the genetics domain is a complex, multi-level process. Some additional factors influencing problem solving included: strategic knowledge, conceptual knowledge, maturation, motivation, learning style, cognitive preferences, verbalization, and perception.

The research on concept interpretation and problem solving of experts and novices contains elements common to a variety of scientific domains. The findings from this study supported generalizations from previous research on expert and novice behaviors. The findings from this research study indicated that verbalizing domain specific knowledge may contribute to successful problem solving. Successful performance in problem solving in genetics using CATLAB appeared to necessitate the use of description sequences (especially quantitative observations). The use of description sequences at the onset, during, and toward the termination of problem solving may have led to the recognition, identification, and acquisition of data (knowledge) by successful subjects. This finding was consistent with Sternberg's conclusion (1986) that knowledge acquisition is the factor distinguishing expert performance from novice performance. Describing observations (such as kittens' appearances) may be a key factor in knowledge acquisition. This factor may represent a major step to successful problem solving performance.

The problem solving behaviors of subjects and the intersection of these behaviors with two classes of genetics concepts during problem solving were examined. The findings revealed that certain problem solving behaviors, sequences of behaviors, and classes of genetics concepts are verbalized more frequently by successful problem solvers than by unsuccessful problem solvers. The successful problem solver may draw upon stronger linkages formed between the supporting structures of problem solving sequences and concepts. The researcher synthesized conclusions from this study and other studies (Hackling, 1986; Collins, 1986; Sternberg, 1986) into a problem solving model (representation) of components and relationships between components which contribute to and predict successful problem solving in genetics.

A Genetics Problem Solving Model

The results from this study provided the basis for the synthesis of a prototype model for genetics problem solving. This model is based on the conclusions about problem solving behaviors and the genetics concepts employed by successful and unsuccessful subjects.

Attributes of the Model

During problem solving, the successful problem solver may use sequences of behaviors supported by a superstructure (Figure 9). As the problem solver proceeds from initiation to termination, he uses those [description] sequences and concepts to extract relevant information with which to solve the problem. The superstructure represents a composite of many pathways from which the problem solver may choose. Following various pathways may result in successful problem solving, whereas following other pathways will result in the problem solver using or relying on more fragile substructures. These substructures (Figure 10) may not be linked together as strongly as the overall superstructure. If the problem solver elects to use a pathway where gaps or weaknesses exist within the sup structure, he may have to "jump" from one supporting substructure to another substructure without adequate support of problem solving strategies, concept use, motivation, and so forth. The supporting substructures may consist of description sequences, entity concepts, property concepts, concluding sequences, motivation, or learning style. Links between the substructures may result in stronger ties between parts of the superstructure and and in more stable support for the superstructure.

This model may assist in explaining what occurs when a problem solver initiates problem solving by selecting a path along the surface of the superstructure. As the problem solver progresses toward a goal, he must use various substructures to support his travel along a particular pathway toward the problem solution. He may encounter alternative pathways which lead toward the solution more quickly, or he may find pathways which return him to the starting point or digress toward another problem. The problem solver must decide which path to select along the most stable supporting substructures. If he chooses a substructure which is not securely locked into place (e.g. interpretation of data), he may continue toward problem resolution with insufficient support or may use alternative support substructures from which to reach the end of the pathway. The successful problem solver may progress from initiation to description sequences to specific genetic concepts to conclusion sequences to description sequences to termination.

The unsuccessful problem solver may employ several pathways, such as: (1) initiation to conclusion sequences to general genetic concepts to conclusion sequences to termination or (2) initiation to conclusion to general genetic concepts to termination (Figure 9). The pathways employed by unsuccessful problem solvers may reflect the selection of substructures which are inadequately supported or linked to the superstructure. The unsuccessful problem solver attempts to use a weakened superstructure during problem solving. This study reported that unsuccessful problem solvers did nor rule our all possible explanations to account for the data generated. This characteristic of unsuccessful problem solvers may have be due to subjects drawing upon inadequately supported substructures during problem solving. If the unsuccessful problem solver uses a weak substructure (e.g. segments of the description sequences), he would nor not be alert to particular signals within the data. Such behaviors would result in "gaps" during data interpretation, and could account for unsuccessful problem solvers omitting all possible explanations for data patterns.

The findings reported in this study may reflect situations where successful problem solvers can utilize a variety of approaches (pathways) and draw upon the supporting substructures of quantitative or qualitative problem solving sequences and general or specific genetics concepts to investigate hypotheses. These two substructures represent parts of the framework upon which the superstructure is built. The description sequences may be the strongest links within the substructures. Other sequences (strategies) may represent the weakest link to the superstructure. Underlying the superstructure may be units (substructures) of motivation, learning style, and other substructures. These substructures may comprise an inner supporring ring for other substructures (problem solving sequences) or may be linked within the same level to other substructures.

Further research is needed to elucidate the linkages and levels of all the variables affecting successful problem solving. For example, one area of research requiring closer examinination is the intersection of genetics concepts and successful problem solving strategies. One of the successful problem solvers in this study verbalized a greater percentage of general genetics concepts than more specific genetics concepts. This suggested that the subject drew greater support from the problem solving sequences (description substructures) than from the specific genetic concept substructure during problem solving. The assimilation of information within existing problem solving frameworks organized by the learner may result in the modification or formulation of new links within the framework. These new links may then form stronger associations with other subunits (substructures) within the overall problem solving framework (superstructure). The links between property and entity concepts are not clearly established. The contribution and balance between the factors which influence problem solving need to be determined in subsequent studies.

Gaps between the substructures (e.g. description strategies and property concepts) may be responsible for unsuccessful problem solving. Examining the substructures which learners use during problem solving can add information about the nature of the connections between the substructures and the connections between the substructures and the superstructure. For instance, examining the problem solving behaviors and concept use of subjects along a continuum from least successful to most successful problem solver may supply data about how various levels of learners construct and utilize the substructures within the larger superstructure. Unsuccessful problem solving may be the result of gaps or a disorganized aggregation of substructures within the superstructure. For example, the predominant use of combined or abbreviated versions of problem solving sequences by unsuccessful subjects may be the result of random aggregates within the substructures or a random ordering of the substructures.

The less successful problam solvers in this study utilized the description sequences which the successful subjects employed. Less successful subjects also used a greater percentage of entity (specific) genetic concepts than the least successful subjects used. This may be explained by the random organization of substructures of the less successful subjects. The less successful problem solvers may have the necesary problem solving sequences (description sequences) locked within the superstructure, but the concept substructures may be more loosely or randomly ordered than the concept substructures of successful subjects.

Another explanation for unsuccessful performance in problem solving may be due to the organization of subunits within the substructures. For instance, the substructure of genetic concepts may contain a randomly dispersed or incomplete set of components (aggregates). The aggregates represent the class of entity concepts or property concepts. If the problem solver has an incomplete or disordered set of aggregates, he may not be successful during problem solving. The problem solver may have a complete set of entitiy concepts and employ those concepts during problem sovling, but still not perform successfully (e. g. the unsuccessful expert).

Additional research studies need to be conducted and focus on why certain subjects (students) do not appear to progress from unsuccessful to successful performance. It may be that certain unsuccessful subjects lack or do not employ an organizing element which aids in ordering the substructures during problem solving. These individuals may continue using disordered substructures even when confronted with situations where they realize convergent thinking or problem solving is required for successful performance.

Another area needing further examination is the intersection of the role of logical thinking structures with problem solving and concept interpretation. This study suggested that there are important intersections between genetics concepts, problem solving, and logical processing.

Limitations of the Model

The genetics problem solving model raises many questions about the nature of genetics learning and problem solving. For example, questions about the intersection of problem solving strategies with genetics concepts used to solve problems successfully require thorough examination. Research is needed to analyze how the exclusive or predominant use of certain problem solving strategies (such as description) in conjunction with the use and interpretation of particular genetics concepts (entity or property) may lead to successful problem solving. Research studies in progress are focussing on this area.

The model proposed in this study does not explain how the use of genetics concepts or problem solving skills relate to the development of logical structures in successful and unsuccessful subjects. The development of formal reasoning, in areas such as probability or controlling variables, may be a driving organizer which contributes to the ordering of the substructures. The mechanisms driving the construction of a learner's superstructure need to be elucidated, characterized, and examined more thoroughly. The genetics problem solving model described in this study requires more detailed examination. As more data are generated by studies of the nature described in this dissertation, researchers will have a broader empirical base from which to examine and assess the usefulness of previous and current genetics problem solving models. Subsequent studies are being planned to generate more information describing genetics problem solving and to contribute to the evolution of a problem solving model.

Limitations of the Study

This non-experimental study was designed to investigate genetics problem solving using a naturalistic methodology. The factors affecting the reliability and validity of naturalistic research also applied to the constraints operating within this study. The major considerations affecting the reliability and validity of the present study included the following:

(1) the use of verbal data as reports may have altered or masked subjects' actions or speech.

(2) the absence or presence of the researcher may have influenced subjects' performances.

(3) novelty effects relating to the computer or the simulation may have interfered with or distorted subjects' performances.

(4) the range in ages of the research subjects may have resulted in maturational differences.

(5) the reliability and validity of the coding systems employed in data analyses required greater consistency. The codings performed by another science educator yielded an eighty percent agreement rate.

Implications for Instruction: The Role of the Teacher

The conclusions based on data analyses reported in this study suggest the following implications for instructional strategies used by teachers.

1. Teachers should have students verbalize qualitative and/or quantitative observations during problem solving. For instance, teachers could have students work together in small groups while solving problems.

2. Teachers should provide opportunities for students to develop and practice observation skills and inference skills during problem solving.

3. Teachers should employ appropriate teacher responding behaviors after observing students' perceptions, organization and analysis and interpretation of data, and approaches toward problem solving.

4. Teachers should ask leading questions that help students make more sensitive observations, clarify their understanding of concepts and relationships, and investigate particular hypotheses more effectively.

5. Teachers should stress the importance of verbalizing descriptions during all phases of problem solving. This may encourage students to develop abilities to discriminate key components or signals within the data generated.

6. Teachers should provide opportunities for students to process data, search for patterns

within the data, and examine the patterns for evidence to corroborate a concept or principle.

7. Teachers should provide opportunities for students to experience and to investigate concepts through more meaningful and intellectually appropriate learning experiences.

8. Teachers should have students justify their explanations and confront students with alternate views of data or ways of generating solutions to problems.

By interacting with students and probing the reasoning behind their hypotheses and interpretations, teachers can promote the use and generation of alternative approaches in problem solving to guide students' to successful problem solving. Thus, teachers can become more responsive to their students' individual learning styles and characteristics. By gathering data about students, the teacher can make inferences regarding students' problem solving strategies and probe students' rationale and understanding during problem solving. This information could help teachers identify problem solving behaviors, sequences, and strategies characteristic of successful or unsuccessful problem resolution.

Teachers should attempt to diagnose students' problem solving approaches and strategies to determine the learner's use of strategic knowledge and the rationale driving the use of that strategic knowledge. The findings from the research study reported here showed unsuccessful problem solvers attempted to resolve a problem by using a random or disjointed approach. These problem solvers may have overlooked specific cues within the data patterns. This behavior may be due to their inability to extract pertinent or subtle cues from observations. The data from this investigation indicated that students interpreted data and underlying parterns within their framework of scientific explanations. When unsuccessful students were confronted with discrepant data or explanations of phenomena, they maintained their view of the phenomena. Students can be confronted with data and explanations which are inconsistent with their frame of reference. The process of confronting students with discrepant events or alternative explanations may aid students in the reorganization of the problem solving or conceptual substructures elaborated in the genetics problem solving model.

By providing opportunities for students to utilize observation and problem solving skills, teachers can promote the development of linkages between the description problem solving substructures and the conceptual substructures described by the genetics problem solving model.

Teaching Genetics

The intersection of particular classes of genetics concepts with problem solving strategies may lead to successful problem solving performance. Based upon the model proposed in a previous section, teachers should provide opportunities for students to interpret, analyze, and experience the general and specific genetic concepts during a problem solving activity. These experiences can be discussed and processed in a large or small group setting, where students can have input into their ideas on the nature of genetic concepts and inheritance principles. These kinds of learning environments enable teachers to gather information about the conceptual frameworks (and misconceptions) students have about principles of inheritance. Teachers can then stimulate students' growth in conceptual development and problem solving development by suggesting appropriate learning experiences.

Students may become more sensitive to cues within data patterns and extract relevant information. They may select an approach drawing upon more general descriptions, but use description strategies or analyses (quantitative) of the data. For example, students may use description strategies initially to investigate a concept such as dominance. As they generate more data (kittens), patterns of genetic characteristics will emerge from the data. Recognition of these data patterns through description appears to constitute an essential step in understanding the concept. Following recognition and description, students can attempt to extract signals, organize the signals, and draw inferences about their observations. These inferences can provide the bases for forming generalizations about principles of inheritance.

General Recommendations

Examining learners' behaviors, strategies, and rationales during interaction with a specific simulation can enrich the current empirical base of cognitive processes and concept development. The exploratory nature of this study raised many fertile questions on the nature of problem solving and concept development in genetics. The research hypotheses resulting from this study can provide a well developed research agenda to address the recommendations for research responsive to real instructional needs of students. The research study provided a rich source of information about cognitive processes of learners engaged with instructional software.

The richness of information collected can.serve as sources of data for further examination with different organizing schemes (such as prediction skills or modes of learning style preferences). Subsequent naturalistic and experimental research studies enhancing the empirical base of learning and instruction in science education can be extended from the research hypotheses suggested by the data. Researchers can examine the development, evolution, and interaction of genetics concepts during phases of hypothesis testing. Other research areas suggested by this methodology include examining the decisions and implementation of problem solving strategies amployed by learners to test ideas and assumptions. By examining the options subjects select during problem solving, resesarchers can gain greater insight into the mental mechanisms and mental models learners construct and use to explain underlying data patterns. Investigations examining students' conceptual development in topics studied in high school science courses, misconceptions, problem solving, software design and use, and teaching models and instructional strategies are important subjects for further research in science education. In January, 1986, a national conference involving scientists, science educators, cognitive scientists, mathematicians, mathematics educators, and curriculum and technology experts recommended that "researchers need to explore in greater detail such questions as how students develop a world view, reason about new information, and solve problems in science...research in science education should reflect and respond to real instructional needs" (Linn, 1987). By examining the problem solving behaviors and genetics concepts used by learners during problem solving, the science education community can build a stronger empirical foundation from which to respond to relevant instructional needs of students and to understand the nature of problem solving and concept development.

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Table 1. Classification Scheme for Genetics Concepts (Excerpt)

Property Concept	Entity Concept
carrier	heterozygous carrier
chromosome	
conditions	rare condition
	common condition
	genetic condition
cross/mating	backcross
	specific cross
	heterozygous cross
	classes of crosses
	both classes of crosses
dominant	homozygous dominant
	heterozygous dominant
	dominant autosomal
epistasis	
gamete	
gene	dilution gene
	red/black gene
	light and dark gene
	masked gene
	symbols of genes
	dominamt gene
	recessive gene
	probable gene code
	locus
	wild type
	character difference
	genetic unit

Table 2. Problem Solving Sequences

	Sequence										
1	GD	QLD									
2	GD	QLD					SA				
3	GD	QLD						P		SA	
4	GD	QLD					SA			C	GD
5	GD	QLD		C							
6	GD	QLD		C	QLR	QNR	SA				
7	GD	QLD		C	QLR			P	TP		
8	GD	QLD		C	QLR		SA				
9	GD	QLD		C			SA	P	TP		
10	GD		QND								
11	GD		QND				SA				
12	GD		QND					P	TP		
13	GD		QND				SA	P	TP		
14	GD		QND				SA			QND	
15	GD		QND							QLD	SA
16	GD		QND	C			SA	P	TP		
17	GD		QND	C	QLR			P	TP		
18	GD		QND	C	QLR		SA				
19	GD		QND	C		QNR				TERM	
20	GD		QND	C		QNR	SA		TP		

Table 2 (cont.)

21	GD	QLD	QND				SA			
22	GD	QLD	QND	C			SA			
23	GD						SA			
24	GD									GD
25	GD						SA	P	TP	
26	GD			C						
27	GD			C			SA			
28	GD			C	QLR	QNR				
29	GD			C	QLR			SA		
30	GD			C		QNR	SA	P	TP	
31	GD			C		QNR	SA			
32	GD			C			SA			QND C
33	GD			C			SA	P	TP	
34	GD			C				P	TP	
35	OTHER									

GD = gathering data
QLD = describing qualitative observations
QND = describing quantitative observations
C = drawing a conclusion
QLR = explaining a qualitative relationship
QNR = explaining a quantitative relationship
SA = selecting an action
P = predicting
TP = testing a prediction

Table 3. Sequences in General Problem Solving Categories (Percent)

	Subject												
	1	2	3	4	5	6	7	8	9	10	11	12	13
D	50	56	31	45	0	27	0	51	7	40	59	0	38
GD	0	13	31	18	0	0	0	5	14	20	36	25	0
C	50	6	38	0	17	0	0	32	0	20	0	12	0
O	0	25	0	36	83	73	100	15	79	20	4	12	62

D includes describing qualitative and quantitative observations
GD includes gathering data
C includes concluding
O includes other sequences

Table 4 Problem Solvers Clusters of General Problem Solving Sequences

	Successful	Less Successful	Least Successful
Higher% % of Description	8, 11, 12	1, 2, 10	4
Higher % of GD			
Higher % of Conclusion	3	1	
Higher % of Other		13	5, 6, 7, 9

Description refers to qualitative and quantitative description problem solving sequences
GD refers to gathering data problem solving sequences
Conclusion refers to concluding problem solving sequences
Other refers to problem solving sequences not previously described

Table 5. Problem Solving Clusters and Percentage of Concepts

	Successful	Less Successful	Least Successful
Higher % of Property Concepts	11	2	4, 6, 7, 9
Higher % of Entity Concepts	3, 8, 12	1, 10, 13	5

Table 6. Group Means (Percent) for Problem Solving Sequences

	Group			
	Successful	Less Successful	Least Successful	Unsuccessful
D	48	46	16	30
GD	19	8	7	7
C	16	19	3	10
O	8	27	74	53

D = Description sequences means
GD = Gathering data sequences means
C = Conclusion sequences means
O = Other sequences means
[Unsuccessful group includes less and least successful subjects]

Figure 1. Flow Chart of Problem Solving Behaviors

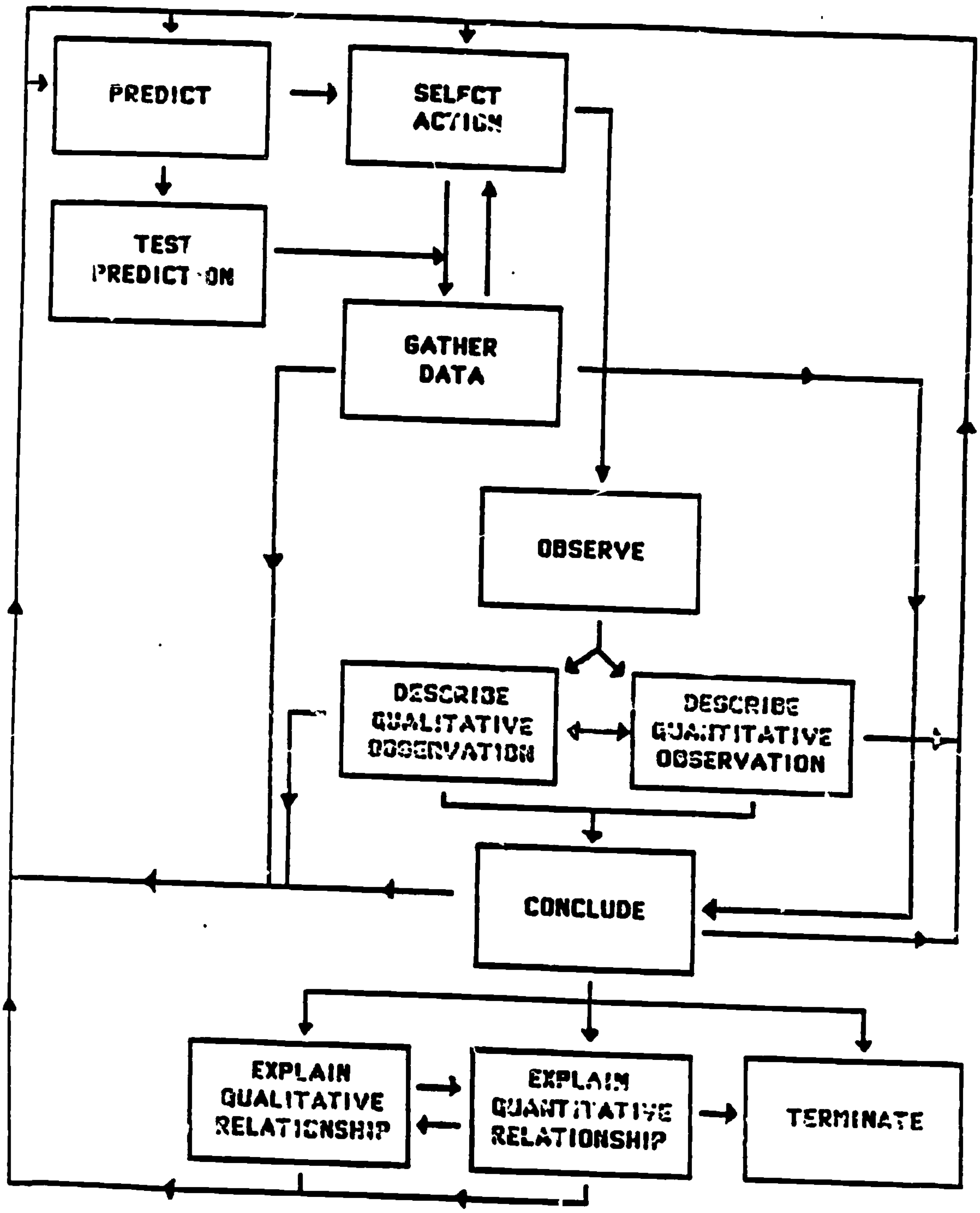


Figure 2. General Problem Solving Sequences of Successful Subjects

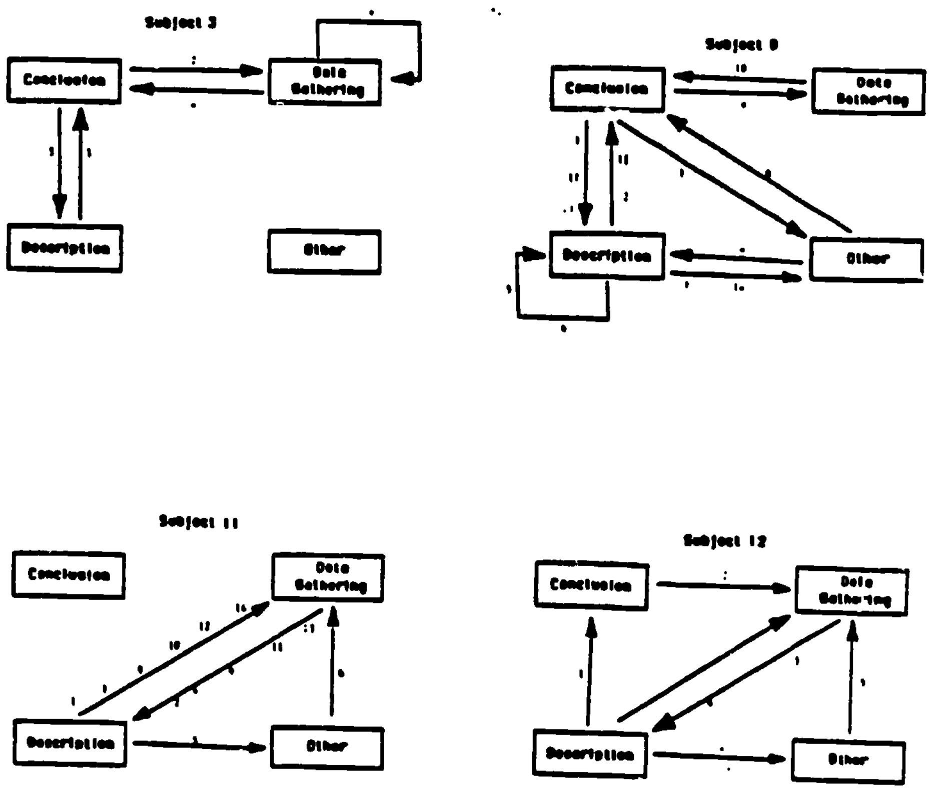


Figure 3. General Problem Solving Sequences of Less Successful Subjects

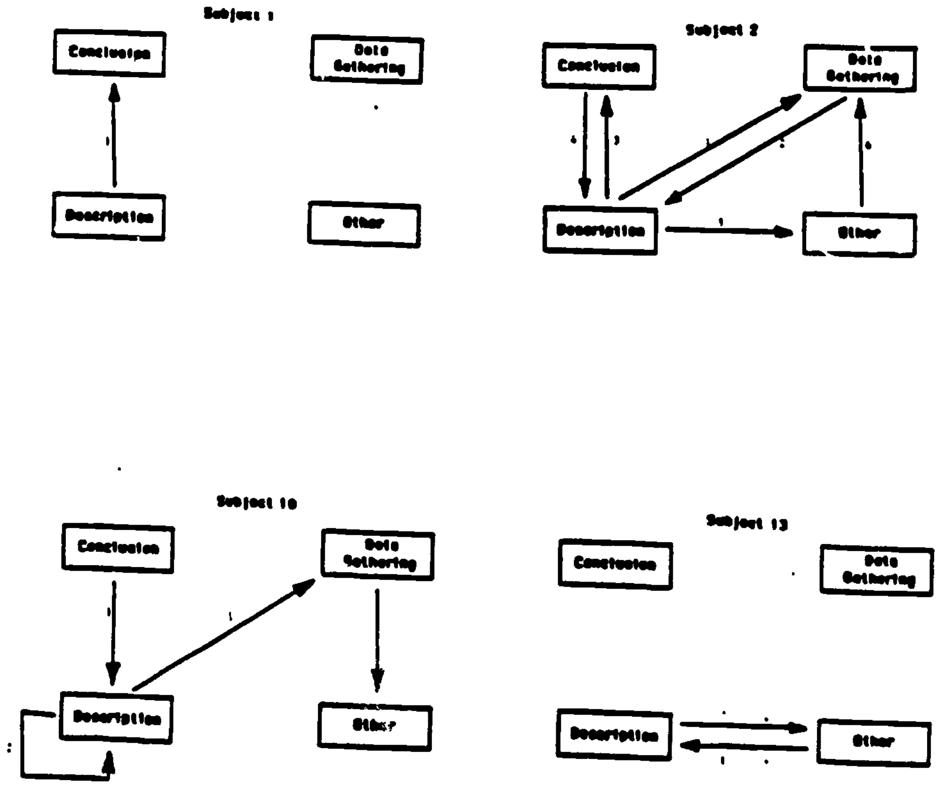


Figure 4. General Problem Solving Sequences of Least Successful Subjects

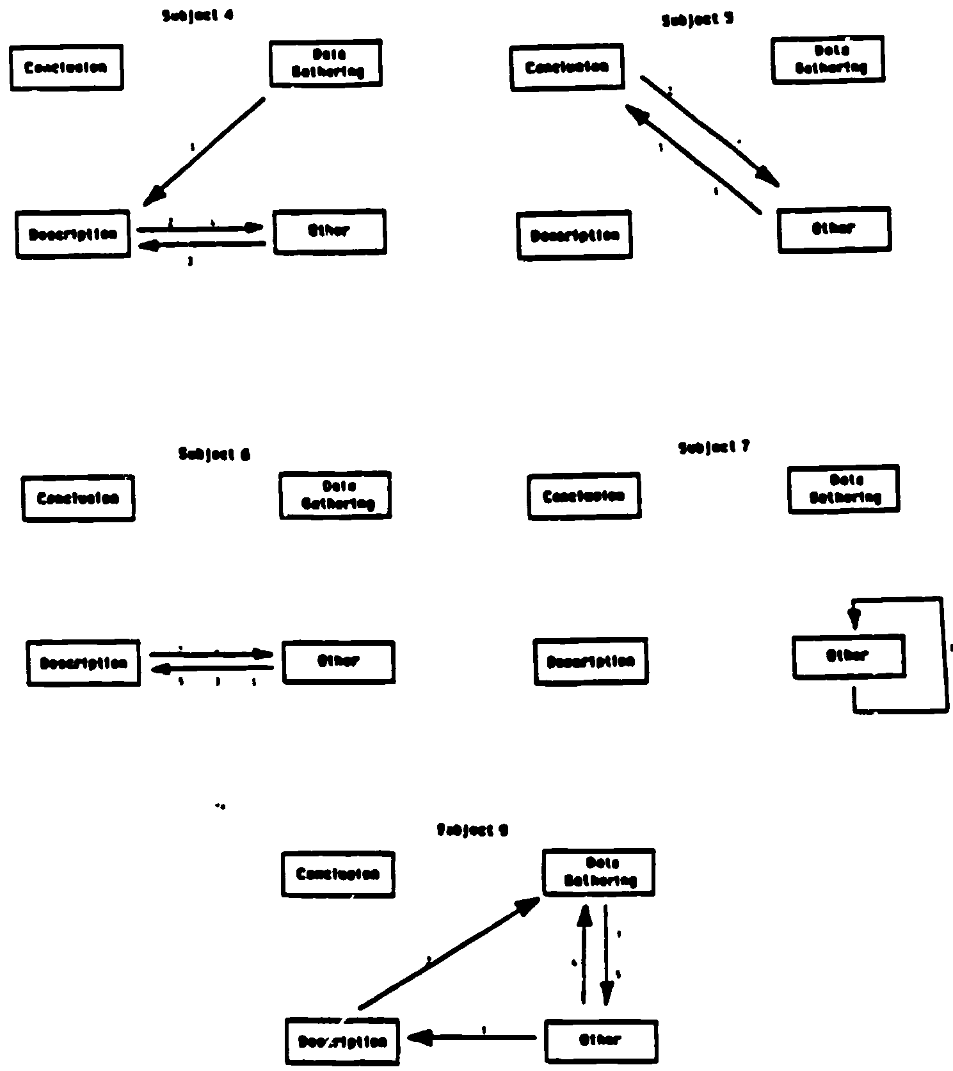
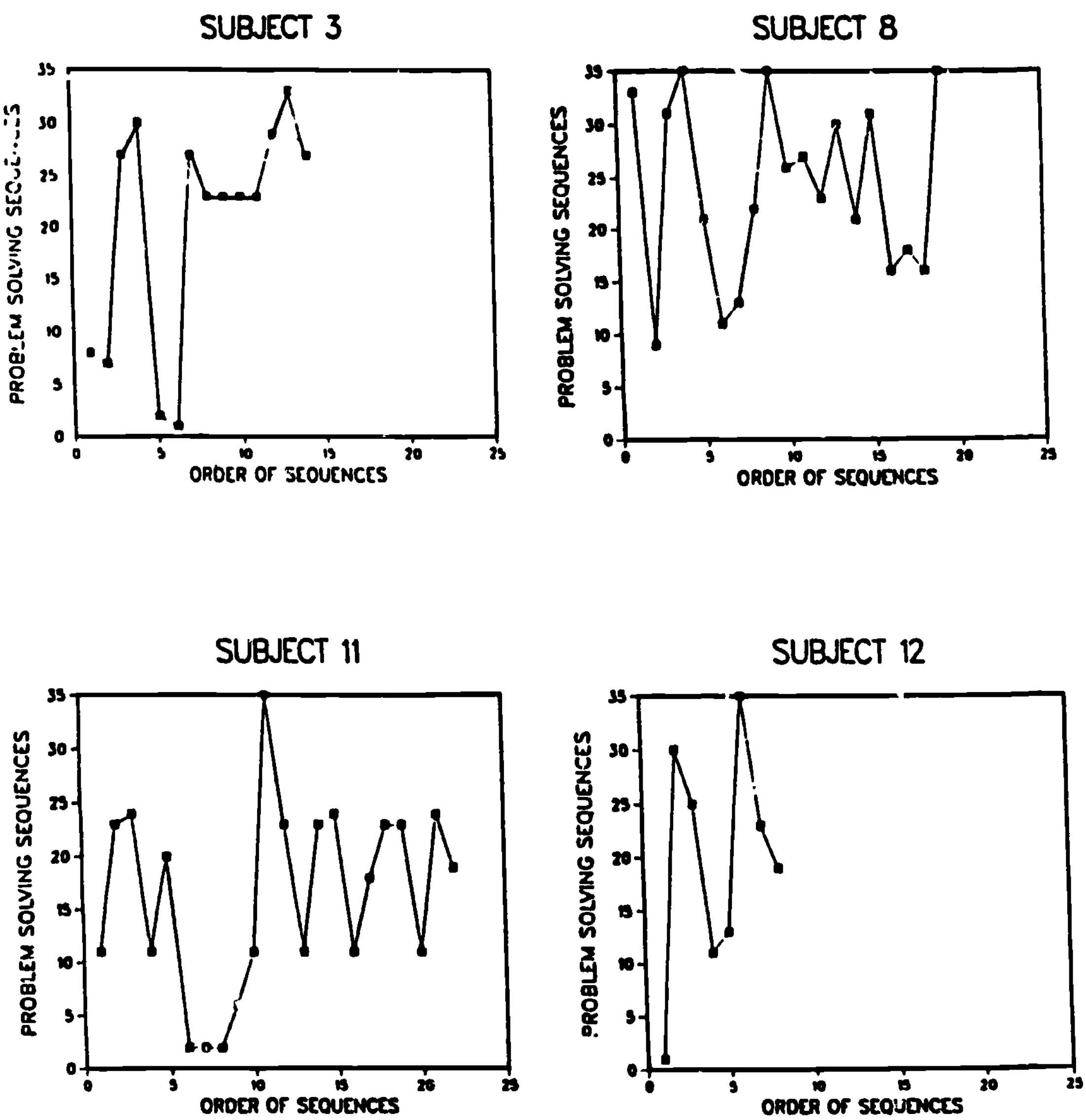


Figure 6. Order of Problem Solving Sequences of Successful Subjects



Problem solving sequences 1-22 were categorized as description
Problem solving sequences 23-25 were categorized as gathering data
Problem solving sequences 26-34 were categorized as conclusion
Problem solving sequence 35 was categorized as other

Figure 7. Order of Problem Solving Sequences of Less Successful Subjects

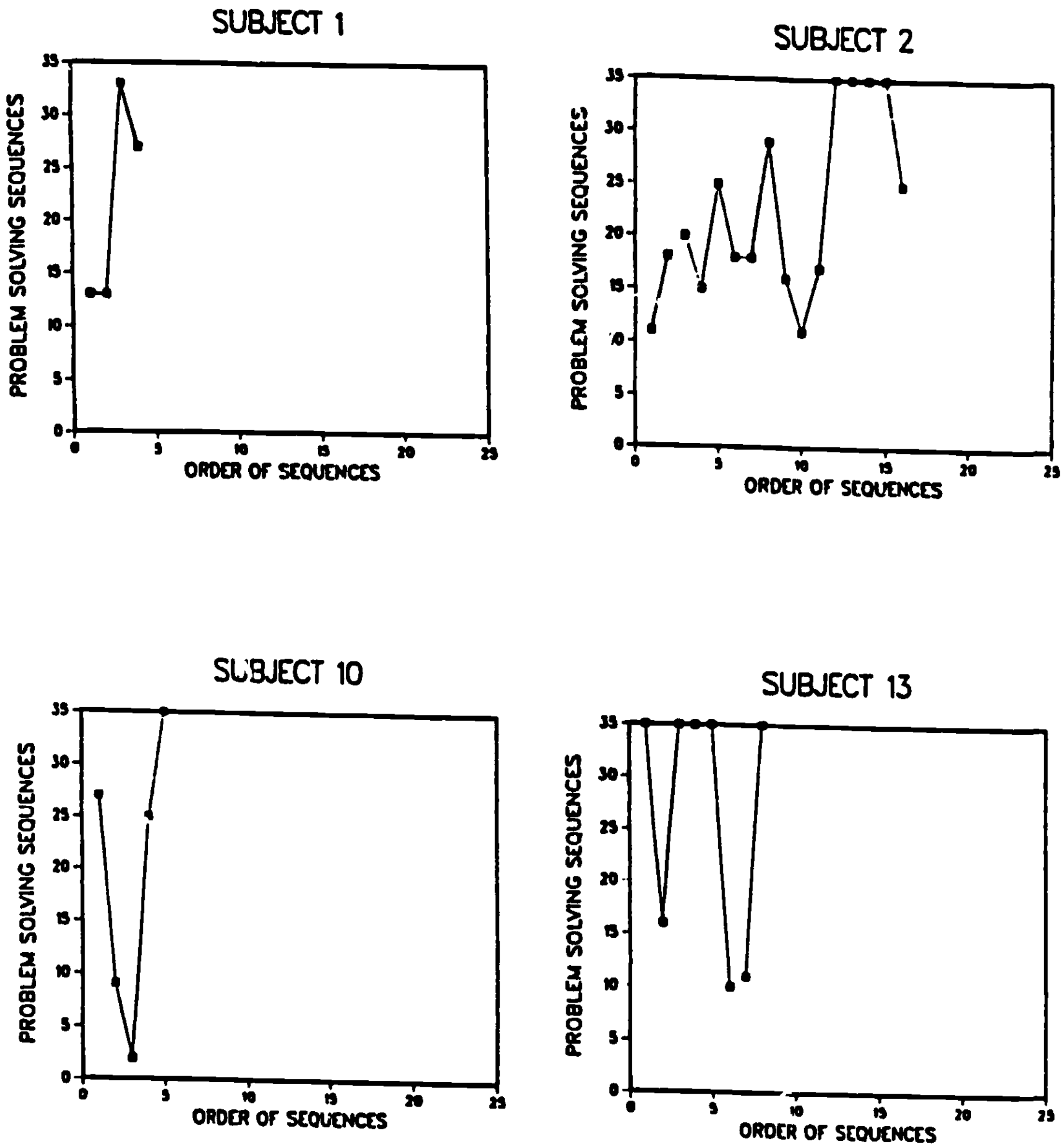


Figure 8. Order of Problem Solving Sequences of Least Successful Subjects

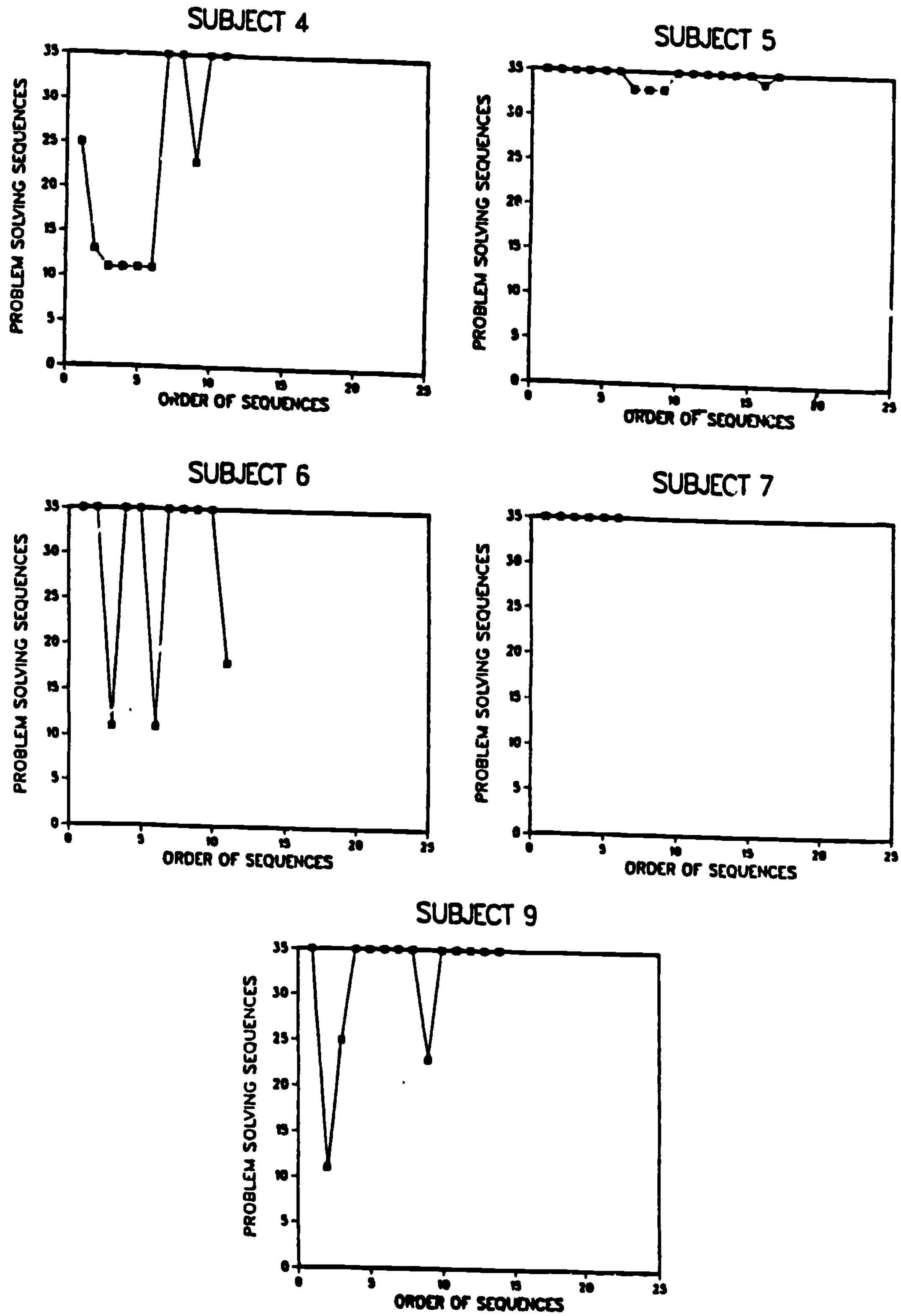
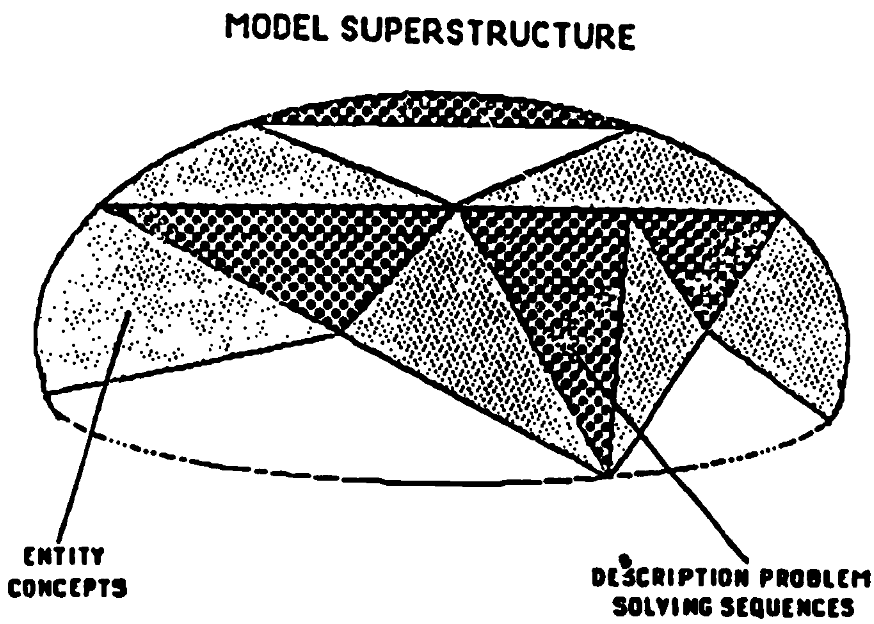
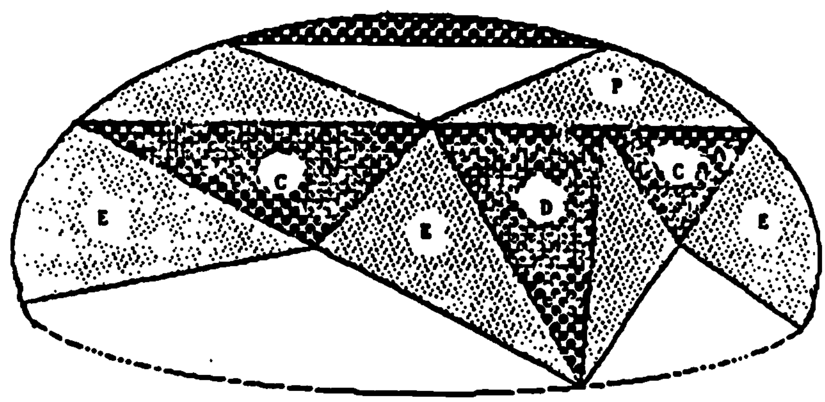


Figure 9. Superstructure of a Genetics Problem Solving Model





Possible Pathways of Successful Subject
C - D - E - C - D substructures

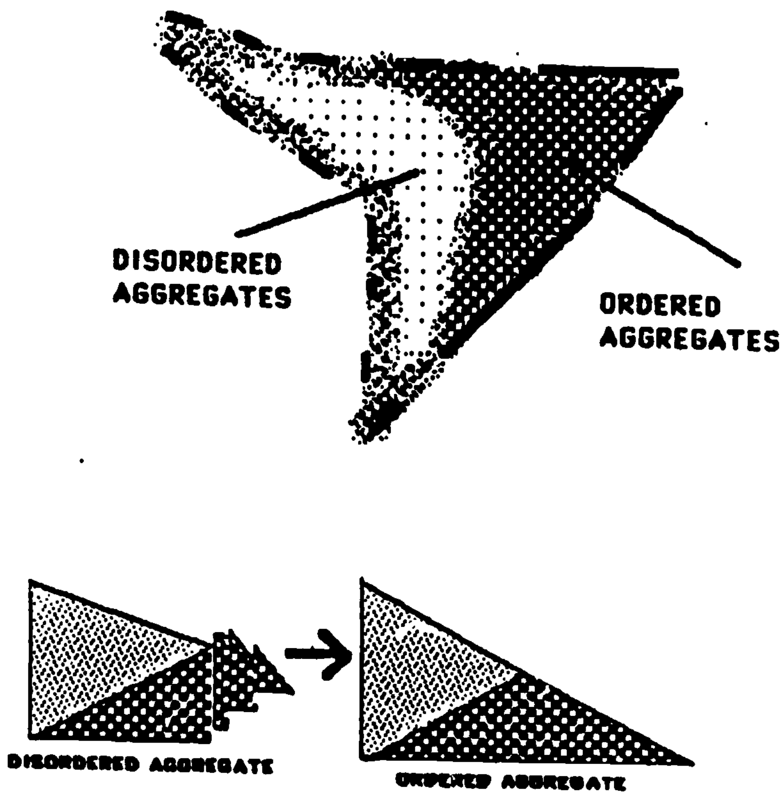
Possible Pathways of Unsuccessful Subject
C - P - C substructures

C - P substructures

E denotes entity concepts
P denotes property concepts
D denotes description sequences
C denotes conclusion sequences

Figure 10. Substructures of a Genetics Problem Solving Model

SUBSTRUCTURES



ORGANIZING FORCE