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The Solving of Biological Identification Tasks by High School Students

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The Solving of Biological Identification Tasks by High School Students

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In the science classroom, teachers often ask students to solve problems. In physics and chemistry, the problems presented to students generally have a preferred method for reaching one correct solution. On the other hand, many of the problems found in biology may involve several paths to a solution, and possibly, reflect a variety of acceptable answers. As such, biological problems are frequently characterized as unpredictable (Mayr, 1985).

In the present study, it is posited that classification schemes can serve as a source of less well-structured or unpredictable problems. Classification skills are frequently listed as objectives of science curricula, yet teachers place little emphasis on having students work with classification or identification problems. One possibility of why teachers do not work with such problems is that the role of taxonomy is seen merely as a convenient way of organizing a large variety of organisms, rather than as a reflection of a more comprehensive conceptual organization. The way in which organisms are classified is quite variable and depends upon how a classification scheme is to be used (Mayr, 1982). According to Mayr, the process of classification has to do with the actual development of organizational schema. Identification, on the other hand, refers to the process of placing individual organisms in an already existing classification scheme. Since classification schema are artificial constructs, the identification of individual organisms within a particular scheme can always contain an element of uncertainty. As such, classification and identification problems often reflect the unpredictable nature of biological problems. Surprisingly, as organized as a classification system may appear, such a system can contain the elements of unpredictable problems. If we want students to work with more realistic (unpredictable) problems that relate to the major organizing concepts of biology, such as those involved in evolutionary theory, then we should consider formulating problems from classification schemes.

In the following sections, the role of classification in biology will be examined followed by a discussion of the categorization of natural objects (including organisms) in memory, the cognitive counterpart of classification. A brief overview of information processing psychology as a model of memory organization and cognition will then be outlined. Since identification, as the term should imply, concerns the solving of problems, an examination of the highlights of the problem solving literature as it relates to biological identification problems will be reviewed.

Theoretical Framework

A characteristic of the structure of knowledge in biology is the classification of information, which includes the taxonomic organization of living organisms. According to Sokal (1974), classification can

> ,... reflect the natural processes that have led to the observed arrangement....achieve economy of memory.....[providefor] ease of manipulation [of information].....[provide for] ease of retrieval of information … [and, most importantly,] describe the structure and relationship of the constituent objects, and...simplify these relationships in such a way that general statements can be made about classes of objects, (p. 185)

Sokal also contends that classifications can act as guiding principles of inquiry. For example, the taxonomic ordering of organisms can give rise to questions about how such relationships began and developed.

The study of classification in the science classroom can become a basis for inquiry, rather than the way classification is typically treated, as a static and factual organization of organisms. Such classification has to do with the way in which organisms are grouped together in terms of sets of relationships. Identification and the process of identifying, on the other hand, refer to the placing of objects in an already existing classification scheme. According to Mayr (1982), classification uses a great number of characteristics in an inductive process of formulating a system of groups, whereas identification uses a few characteristics in a deductive process of placing objects into pre-existing classes.

From the point of view of cognition, the notion of classification is often referred to as categorization. In the early work of Bruner, Goodnow, and Austin (1956) and the more recent work of Rosch, Mervis, Gray, Johnson, and Boyes-Braem (1976), categorization is thought to play a significant role in how information is processed. While, on the one hand, the process of categorization can reduce cognitive strain (by reducing the number of attributes), it can also increase cognitive strain. For example, if a large number of attributes need to be kept active in memory (see discussion of working memory later in this section) while considering very fine discriminations, the task of keeping that information available is difficult for the individual.

The research of Rosch et al. (1976) indicates that people do categorize objects in their environment. Essentially, she and her associates found that there are three hierarchical levels of categories: (a) superordinate, (b) basic, and (c) subordinate. Superordinate categories are the most inclusive and the least discriminable, while subordinate categories are the least inclusive and most discriminable. Basic categories, however, are considered to be the most cognitively economic in terms of inclusiveness and discriminability.

Related to the process of categorization, one of the major issues facing researchers is how such learning takes place, or, in other words, how knowledge is represented and stored in memory (Preece, 1978; Stewart & Atkin, 1982; Resnick, 1983). According to Resnick, there are three major components to the learning process. First, learners construct knowledge by looking for patterns (which includes the construction of naive or misconceived theories). Second, comprehension involves the knowing of relationships between different clusters of knowledge. Third, all learning is dependent upon what is already known (prior knowledge). While the official knowledge of a particular discipline can be mapped (Ziman, 1985), the way that knowledge is represented and stored in human memory, as well as what is stored, is of great importance in understanding how learning and problem solving take place.

Much current research into learning is based on the theoretical framework of information processing psychology. Central to the information processing theory is the distinction between long-term (LTM) and short-term or working memory (WM). Long-term memory is a more or less permanent store of information (Anderson, 1976, 1983). Longterm semantic memory contains declarative knowledge and processes or procedural knowledge. The basic unit of declarative knowledge is referred to as a proposition. Each proposition is linked or related to others, resulting in what is hypothesized as a propositional network (Collins & Quillian, 1969; Collins & Loftus, 1975; Anderson, 1976, 1983).

As propositions are activated they are, in a sense, placed in working memory. Most newly received information is temporarily stored in WM, whether that information comes in through the senses or from LTM. It is in WM that ideas are manipulated and related to other ideas (Anderson, 1976, 1983). Active portions of propositional networks are stored in WM along with other propositions in the process of being constructed. The critical characteristic of WM is its limited capacity. Only five to seven items of information or propositions can be held in WM at any one time (Miller, 1956). The capacity of WM is a critical factor in the size of the problems that can be dealt with at any given time. If a problem containing a lot of new information is presented to a subject, the capacity of WM will be put under a great deal of strain to keep that information active. On the other hand, if the information in the problem is well-known to the subject, the WM representation of the problem will need only to contain certain key points that act as pointers to the information already understood and stored in LTM. The process of representing larger concepts and clusters of information is known as "chunking." In other words, a number of related propositions in memory can be represented by a single proposition. For example, the concept "mammal" or "predator" can represent a large array of information to the biologist. Rather than having to maintain all of the characteristics of either of these two concepts active in WM, the biologist can simply use these terms to represent the array of characteristics.

The way in which knowledge may be organized in memory points to a similar notion concerning the knowledge structure of specific domains. A domain is characterized by frameworks of theories and' concepts that guide the processes of inquiry (Schwab, 1964; Shavelson, 1974). Inquiry is concerned with the solving of problems that arise out of a specific domain of knowledge. Therefore, problem solving in science is related to the specific domain of concern and to the way the knowledge of that domain is represented.

Most research and development in problem solving has focused either on general problem solving skills (Frederiksen, 1984; Larkin, McDermott, Simon, & Simon, 1980; deGroot, 1965; Sweller & Levine, 1982; Larkin & Reif, 1976) or on problems in the physical sciences and mathematics (Frederiksen, 1984; Clement, 1979; Larkin, 1979; Simon & Simon, 1978; Larkin, McDermott, Simon, & Simon, 1980; Chi, Feltovich, & Glaser, 1981; Greeno, 1978a; Greeno, 1978b; DeCorte & Verschaffel, 1981; Gabel, Sherwood, & Enochs, 1984). In biology, the only topic to receive much attention in problem solving research is genetics (Stewart, 1983; Good, 1984; Smith & Good, 1984). Problems in the above areas tend to be characterized by one right answer and a definite sequence of problem solving steps. According to Simon (1978), problems with such characteristics are described as "well-structured" problems, as opposed to "ill-structured" problems. Frederiksen (1984) defines well-structured problems as, (a) being clearly formulated, (b) having a known algorithm, (c) having specific criteria for evaluating the correctness of the solution, and (d) having one correct answer.

Ill-structured problems, on the other hand, are defined as, (a) not being clearly formulated, (b) lacking procedures that guarantee a solution, (c) lacking specific criteria for evaluating the correctness of the solution, and (d) possibly having more than one correct answer. In addition, because ill-structured problems tend to be more complex, it is frequently difficult to know when a solution has been attained.

Frederiksen (1984) points out, however, that there is no clear cut division between well- and ill-structured problems. Problems tend to fall along a continuum. He has labeled problems that lie between the two extremes as "structured problems requiring productive thinking." In general, the problems that fall along the middle of the continuum are similar to well-structured problems, but require the problem solver to generate procedures for manipulating information in ways necessary for reaching a solution. Most problems presented to students in school tend to be well-structured. In biology laboratories, for instance, students have explicit steps to follow and one correct answer to find. Unfortunately, many of the domains of biology and their assortment of research problems are not so well-structured. In addition, most of the research on problem solving has involved only well-structured problems, as well (Greeno, 1980).

The procedures involved in solving problems of any structure are of two types: (a) algorithmic and (b) heuristic (Cyert, 1980). Algorithmic procedures contain a sequence of steps that is highly structured and relatively inflexible. Heuristic procedures, on the other hand, tend to be more global in their applications, because of the flexibility inherent in the way in which they can be applied by the individual. Examples of heuristic procedures include: (a) means-end analysis, (b) hypothesize-and-test, (c) use of analogs (replacement of original problem with an abstracted version), (d) dividing the original problem into sub-problems (Frederiksen, 1984), and (e) a variety of domain-specific heuristics (Scandura, 1977).

Other distinctions in the methods of problem solving include the difference between weak and strong methods. As Simon, Langley, and Bradshaw (1981) describe,

> ...weak methods [are] problem solving techniques of quite general application whose generality is assured by the fact that they do not use or require much prior knowledge of the structure of the problem domain....strong methods [are] powerful techniques that are carefully tailored to the specific structure of the domain to which they are applied, (p. 5)

Simon et al. classify generate-and-test (or hypothesize-and-test), means-end analysis, and heuristic search (process of modifying previously tried solution possibilities) as examples of weak methods of problem solving. Weak methods tend to be characteristic of novice problem solvers; however, they are useful to experienced problem solvers when working with novel situations or new knowledge domains. Weak methods are expected to be more useful in working with ill-structured problems, as well. Strong methods, on the other hand, may involve emphases on inferential thinking strategies and on more domain specific procedures.

The knowledge or information available to the problem solver plays an essential role in the solving of problems. As Greeno (1980) points out, "all problem solving is based on knowledge" (p. 10). Understanding how knowledge is stored and processed by the individual is, therefore, important to understanding how problems are solved. In science education research, Novak and Gowin (1984) add that both the knowledge structure of science and cognitive theory play an important role. In fact, Novak and Gowin note, cognitive science "...places central emphasis on the role that concepts and conceptual frameworks play in human construction of meaning" (p. 1).

In light of the limitations of WM and the way in which information is stored and processed in memory, Shulman and Carey (1984) refer to the individual learner as "boundedly rational" due to the constraints of their own information processing capacities. They continue that, "because we lack the cognitive capacities to apprehend the world as it is, we are forced to construct representations of that world and to engage in thinking and reasoning within the confines of those constructions" (p. 508). In other words, the representations are simplifications of what we perceive. The processes that are responsible for developing the representations are based on prior knowledge, the structure of the propositional networks and embedded productions. In the language of problem solving, problem representations are referred to as "problem spaces." The "task environment," on the other hand, is the perceived situation which is then translated into the problem space (Newell & Simon, 1972; Frederiksen, 1984; Shulman & Carey, 1984).

When students are presented with a problem to solve they are faced with a demanding task. The limitations of WM require that the problem be represented in a way that takes up very little space and, at the same time, includes all of the relevant information. The representation must be stored in LTM in an easily accessible fashion or be kept active in WM. The information in the problem representation must be related to prior knowledge. Both the new and the old information must be manipulated through various processes (i.e., inferring and other cognitive strategies) in such a way that an answer (or answers) to the problem is generated. The entire task is one that demands a great deal of knowledge and skill on the part of the problem solver.

In order to develop a working knowledge of problem solving in biology education, educators need to consider, (a) the structure of the knowledge of the particular domain or domains (identification, in the present study), (b) the form in which students' represent and store the information that is presented to them, (c) the structure of problems, (d) the various heuristics of problem solving, and (e) the way in which students represent and process the information in problem solving tasks. The relations and interplay between these five aspects comprise the context of student problem solving in science. In essence, such a view represents a new view of science education.

A brief review of the problem solving process may help to clarify this new view of science education. In considering a problem that is not well-structured, but is in the realm of structured problems requiring productive thinking, we can expect certain items of information from the conceptual framework of the discipline to be included in the problem statement. It is then expected that the student will make a connection between the Given information and related information in his or her memory. A representation of the problem will then be formed in WM, which will consist of propositions from LTM and new information from the task environment (statement of the problem). At this point, various productions (automatic processes) will manipulate and transform the information in WM. If productions are unavailable, the student may have various strategies stored as declarative knowledge, which could be brought into WM and followed step by step in a slower and more conscious manner. Upon solving the problem, the solution would result in one or more new propositions which would then be added to the propositional network in the vicinity of the propositions used to help solve the problem.

In working with identification tasks, students are required to discriminate between basic and subordinate level categories. At the same time, they are required to represent the task environment, draw on prior knowledge, and manipulate the information in WM in such a way that a solution is generated. The major research problem involves how students represent identification problems, and what strategies they use in defining the problem spaces and in reaching solutions.

Method

For the purposes of the present study, the intent was to select students who had taken an introductory biology course within the past two years. Therefore, the subjects were selected from two sections of a biology II class in a metropolitan area high school. Twenty-eight students who had permission to participate completed a series of word association tasks and a short questionnaire. For participation in the problem solving tasks, the four most varied subjects were selected based on the results of the word association task and on the grade average of the first three exams in the course.

The selection of subjects for the problem task focused on finding the most variety among students. From the results of the word association (WA) task (see subsection below for more details) and the results of the first three unit exams in the biology II class, four different students were selected. More specifically, from the results of the exam, students with the highest and lowest average scores were selected. Selection from the word association task discriminated among students who listed the most typical vs. the least typical examples of animals under each of the stimulus categories.

Two weeks or more prior to the introduction of the problem tasks each student was asked to respond to a series of animal categories. The major result of the word association task involved the typicality of listed examples. Both Battig and Montague (1969) and Rosch et al. (1976) worked extensively with the typicality ratings of examples listed under a large variety of stimulus categories. In a similar way, typicality ratings for each example listed in the present study were determined. The average of all typicality values for all examples listed by each individual resulted in a typicality rating for each student.

Two students at the extremes of typicality were selected. Both students had approximate ratings of one standard deviation on either side of the class mean. No ties existed. Ties among students did exist for the criteria of grades. In one case, students were selected by eliminating those furthest from the mean of typicality scores (0 rating). In the second case, where grades (A's) and typicality ratings were similar, the student with 100% correctly categorized examples was chosen.

Task Environment

The task environment in the present study consists of a computer-based biology problem solving game: *Animal Tracks* (Bloom, 1985a). The goal of the game was to determine the type of animal (according to the conclusions of Rosch and others [1976] the type of animal corresponds to a subordinate category) described by a series of clues. Each Given (clue) was selected by the student from one of five categories: (a) food, (b) air, <c) water, (d) reproduction, and (e) protection. A sixth clue (ecology-behavior) appeared after the first five clues had been seen and a correct response had not been entered. After each clue appeared the student had the opportunity to pass and select another clue or to guess the animal.

The Givens are based on a theoretical framework of evolutionary biology and ecology. Each Given describes some feature of how the animal in question is adapted for survival in terms of the framework of the clue category. The information contained in the Givens consists of one to three propositions (see excerpts of the transcript in Table 5 for examples of Given statements).

As the student begins the game (identification tasks), each Given adds new information to the task environment which is transferred in some form to a problem representation in the student's WM. The structure of the problem (as discussed by Frederiksen, 1984) also changes. For the, most part, the addition of new information creates a more well-structured problem space. Prior and alternative conceptions can, of course, influence the degree of structure for the individual student. In addition, the order in which the clues are selected varies the structure differently. If the easier clues are seen first by one student, the structure of the problem space at that point will appear more well-structured, than if another

knowledge

student sees the less difficult clues last.

In the study, each student was asked to identify all six animals. The order in which the clues were seen was decided by the student. However, the order of appearance of the animals for each student was the same: (a) frog, (b) squid, (c) jellyfish, (d) bat, (e) dolphin, and (f) penguin.

Table 1

Variables used to encode transcripts.

<u>Conjectures</u>	
conjecture (accurate)	solution (correct)
conjecture (inaccurate)	solution (incorrect)
conjecture (correct)	
<u>Inferences</u>	
definition	interpretation
recall	elaborative inference to a structure
to superordinate category	to a function
to a behavior	to a habitat
to an ecological position	to a process
to a niche	
<u>Repetition</u>	
of a Given	of an interpretation
of an inference	of a conjecture
<u>Sequencing</u>	
elaborative sequencing of encoded variables	
<u>Testing validity</u>	
of conjecture against Given	of conjecture against inference
of inference against Given	
<u>Status comments</u>	
status of problem comment	reference to self (ability)
comment about memory	reference to lack of knowledge
<u>Focusing comments</u>	
vocal hesitation	focusing comment or question

Procedures

Tape recordings of concurrent and retrospective verbal reports were obtained through the "think aloud" technique (Ericsson & Simon, 1984; Larkin & Rainard, 1984). Each verbal report session lasted approximately 45 minutes and began with a short conversation with each student. Instructions for the think aloud technique were read to the student, followed by thinking aloud during a practice problem. The student then read the instructions to *Animal Tracks*. Concurrent verbal reports were obtained during the problem solving sessions.

Retrospective reports included asking students to summarize what they were thinking after each of the six animal problems. More in depth, probing questions were included after the sixth animal, where such questions were not a threat to influencing how and about what students thought.

Data Analysis

The tape recorded verbal reports from the problem solving sessions were transcribed verbatim. The transcripts were then encoded using the variables listed in table 1. A number of graphic representations were constructed from the protocols, including solution path flowcharts and problem representations (see Figures 2 and 3).

Inter-rater Reliability

The reliability of coding the protocol transcripts was determined by comparing the coding schemes of two external raters with the scheme of the researcher. Four sample transcripts (one animal trial from each student) with a total of 262 possible coding items were used in the reliability testing process. Coding comparisons were based upon nine general categories of coding items: (a) no coding response, (b) repetition, (c) conjecture, (d) solution, (e) testing of validity, (f) inference, (g) recall, (h) status comments, and (i) focusing comments. Each external rater was in agreement with the researcher on 72% of the coding items.

A more specific comparison of the percent of agreement on individual coding categories appears in table 2. In general, the agreement between the researcher's coding and the external raters appears to be significant. In the few instances where one rater's agreement percentage was low the agreement with the other rater was high. Where there was disagreement between the researcher's codes and those of the raters, many of these instances can be attributed to (a) the raters' lack of knowledge about biology, (b) the raters' weaker understanding of specific coding terms, such as inference, status comments, etc., and (c) the raters having not experienced the task (*Animal Tracks*), and (d) the raters having not listened to the original tape recordings of the interview sessions.

Table 2

The percent agreement between two external raters and the researcher in coding (based on nine general coding categories) one sample transcript from each of the four students.

	Coding Categories								
Rater	N/R	RPT	SOL	CNJ	TST	INF	REC	STAT	FOC
1	56	94	33	67	86	67	100	77	92
2	75	86	100	83	43	50	0	73	67
# Items	121	48	3	6	7	12	2	22	39

N/R = no response, RPT = repetition, SOL = solution, CNJ = conjecture, TST = test of validity, INF = inference, REC = recall, STAT = status comment, FOC = focusing comment

Results

Strategies

Four primary and two secondary problem solving strategies were evident from the protocols of all four students (see Table 3). The primary strategies included, (a) repetition of Givens and other information, (b) inferring, (c) testing the validity of generated information, and (d) elaborative sequencing. Each of these strategies focused on the manipulation of information in the problem representation. The secondary strategies, on the other hand, appear to be more concerned with focusing of attention on the problem. In general, the strategies are grouped into two broad categories of how they appear in the protocols: (a) focusing comments and (b) status comments.

The repetition of Givens and other information the problem representation is by far the most common primary strategy evident in the protocols of each student. The result of repeating information appears to be two-fold. One, repetition focuses attention on specific propositions during searches of memory for associated information, including potential answers. The second apparent result of repetition is that the information being repeated is kept accessible to WM and active in the student's problem representation. Of all four students, student 10 had the highest percentage of repetitions out of all encoded remarks (see figure 1).

Inferring as an information manipulating strategy seems to include two basic levels of information processing. At a more superficial level, definitions of terms, simple interpretations of Givens, and simple recall of information are considered inferences. For the purposes of the present study, such cognitive behaviors provide information that is not in the Givens, and, therefore, are considered to be inferences.

Table 3
Student problem solving strategies

Primary Manipulative Strategies
Repetition of Givens and other information in problem representation.
Inferring.
Testing conjectures and other generated information against Givens and/or other generated information.
Elaborative sequencing.
Secondary Attention Focusing Strategies Focusing comments.
Status comments.

Cognitive leaps from the information in the Givens characterize inferences at deeper levels of processing. Included among such inferences about the problem animal are, (a) descriptions of the habitat, (b) description of the ecological position, (c) descriptions of some property of the animal, (d) descriptions of the niche occupied by the animal, (e) descriptions of behavior, and (f) identification of superordinate categories. The result of such inferences is that more information is made available to the problem representation. Not only is the proposition of the inference included in the problem representation, but any associated information in memory is potentially accessible. In addition, the scope of the search for a solution becomes more narrowly focused. For instance, if a student infers that a particular animal lives in the water, the field of the search is limited to the set of aquatic or marine animals. Further-more, the particular characteristics of aquatic animals are potentially accessible to the student.

The strategy of testing the validity of conjectures or other generated information is central to the generate-and-test heuristic. The strategy, as opposed to the heuristic, is the specific occurrence of a test of generated information against a Given or other generated information. The observed occurrences of such a strategy included testing, (a) a conjecture against a Given, (b) a conjecture against an inference, and (c) an inference against a Given. As a result of such tests students accept or reject the object of their test.

Elaborative sequencing, as it appears in the present study, is a strategy that links several pieces of information together. The use of such a strategy appears to result in the construction of a more elaborate or extensive image of the problem representation, construction of such an image can in turn affect the search for associated information in memory, specifically a potential answer.

In its simplest form, elaborative sequences consist of a number of repetitions of Given information linked together by a reference to an animal entity. The reference to such an entity is not necessarily a specific conjecture. Rather, it can appear as an effort on the part of the student to connect several pieces of information together. For example, after seeing the last Given in the squid problem, Student 24 says, "has a beak...has water regulatory system...has gills...there's two of 'em." No specific conjecture is evident in the sequence. The student does appear to be linking all of the information together as evidenced by starting each repetition of Given information with the word, "has." "Has" seems to indicate that the student is attempting to develop a problem representation that associates a number of different pieces of information. More sophisticated elaborative sequences contain inferred, as well as Given information.

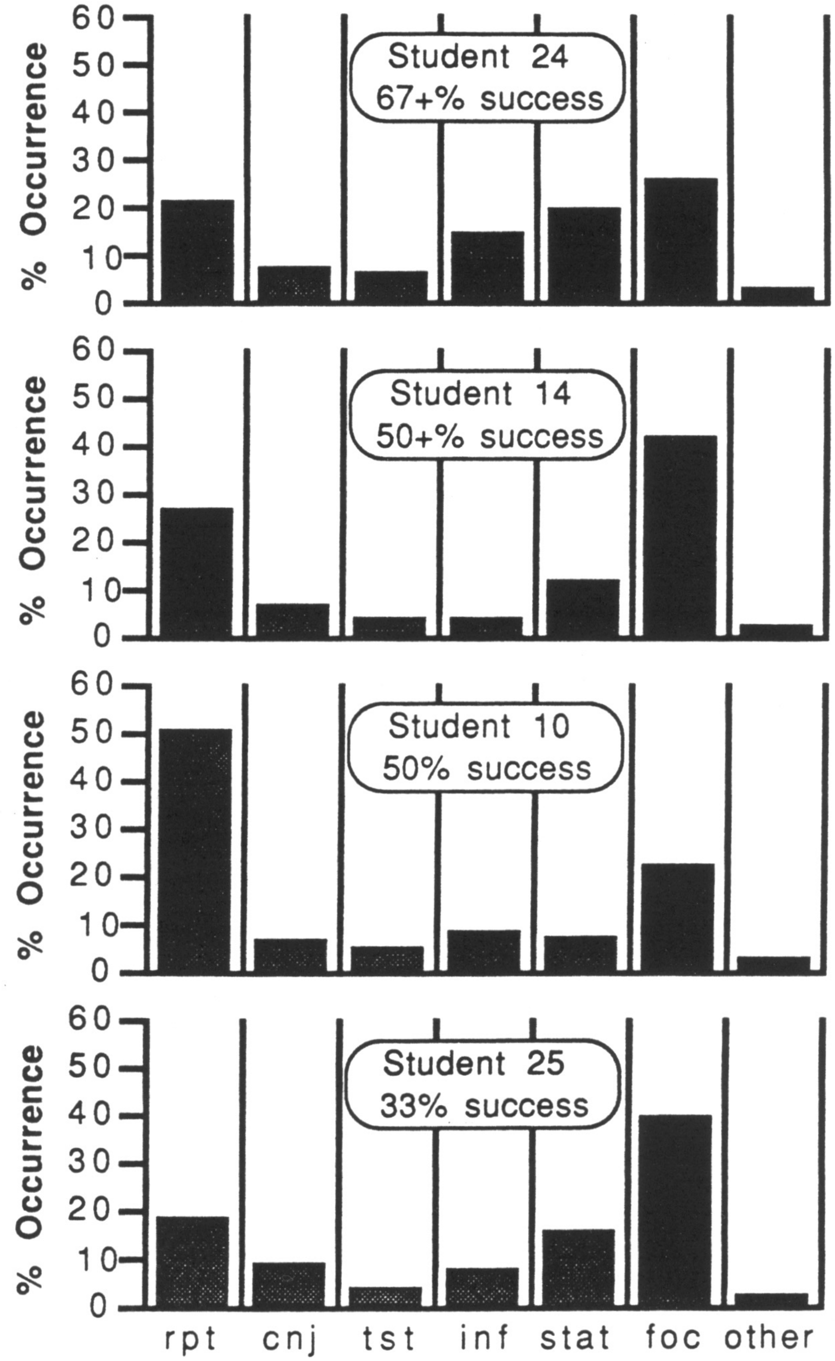

Figure 1. Frequencies of encoded cognitive behaviors.

Focusing comments appear to indicate the focusing of attention on the problem at hand. Such focusing can include, (a) attending to information in the student's own problem representation, (b) attending to Given information, and (c) attending to the search of memory for associations. Since most focusing comments as they are coded in the present study include very simple statements or sounds, it is difficult to determine the purpose they serve. Only focusing questions provide a context for determining their purpose, which is the searching of memory for some sort of association.

However, focusing comments appear to indicate some difficulty with the problem task. If a student is searching memory and vocalizes a focusing comment, he or she is spending a fair amount of time searching for an association. An immediate association is not being made. Attending to the problem representation or Given information, as pointed to by a focusing comment, may indicate that the student is having difficulty in one or more of several ways: (a) understanding the information, (b) keeping the information active in WM, or (c) remembering previously seen Givens. On other occasions focusing comments may indicate points at which the student is trying to (a) make a decision or (b) search for an association to prior knowledge.

Status comments appear to be at the level of metacognition. The student making such statements is evaluating the status of some aspect of the problem solving session, the status of their own knowledge, or a view of their ability. Such comments do not appear to be directly involved in the solving a particular problem, but do appear to indicate the students' own perception of his or her progress.

The frequencies of occurrence of encoded strategies provide a means for describing the overall approach students rely upon to solve problems. Figure 1 displays the relative frequencies of encoded statements and strategies for each student. All frequencies are based on the number of observed items per Given accessed by the student in each trial. The frequencies are, in turn, shown as the percentage of the number of observed occurrences out of the total number of encoded items.

As is evident in figure 1 , Student 10 showed the most reliance on the repetition of information as a strategy in solving the problems (over 50% of all encoded items). Such a reliance on repetition is supported in the ratios of repetitions to the number of conjectures, as displayed in table 4. Since one of the apparent objectives in the problem solving tasks of the present study is the generation of conjectures as possible solutions, the ratio between the frequency of a strategy and the frequency of conjectures can be an indicator of the degree to which the strategy is used.

The frequencies displayed in figure 1 for students 24 and 25 appear to be very similar. Both students have low frequencies of repetitions and relatively high frequencies of conjectures. The major difference between the two students is in the frequency of inferences. Since repetitions are primarily concerned with keeping information accessible to WM and indicative of memory searches, it would be expected that a low frequency of repetitions would indicate difficulty in keeping information accessible. Such is certainly the case for Student 25. However, the higher frequency of inferences for Student 24 compensates for the low frequency of repetitions. By making inferences, Student 24 is actually associating information in her memory to the information in the Givens. Such inferences not only serve to make a great deal of information available to the problem representation, but also serve to keep that information more easily accessible because of its meaningfulness to the student. In other words, in making an inference the student is producing a meaningful association to a set of associated knowledge that that student has constructed in his or her memory. The result of making such inferences is that the repetition of information for successful problem solving becomes less critical. The ratios shown in Table 4 support the relationships between repetitions and the generating of conjectures and between inferences and conjectures. Both students show relatively low ratios between repetitions and conjectures. However, Student 24 displays a consistently higher ratio between inferences and conjectures across solved, not solved, and total trials.

Table 4

Ratios between encoded variables for each student.

Encoded Items	Student 10 50% + correct	Student 14 50% + correct	Student 24 67% + correct	Student 25 33% correct
repetition : conjecture	8.52	4.39	2.55	2.20
testing : conjecture	.83	.61	.77	.38
inference : conjecture	1.28	.71	1.84	.95
inference : repetition	.15	.16	.72	.43
focusing : conjecture	3.67	6.90	3.14	4.58
status : conjecture	1.00	2.16	2.41	1.82

Student Knowledge Characteristics

Analysis of the transcripts reveals two problematic areas of student knowledge: (a) naive concepts and (b) variable degrees of a lack of familiarity with specific concepts and terms. Very few naive concepts are clearly exhibited. On the other hand, a lack of familiarity with information in the Givens is more common.

The naive conceptions expressed by students are mostly concerned with the characteristics of specific organisms. Student 14 considers dolphin as having gills like fish. However, in the WA tasks she lists whale (an acceptable correct answer in the identification task) as an example of mammals. Student 24 associates buzzard as being a predator, but is not sure. Both Students 24 and 25 do not know penguins have feathers. The only other type of naive conception involves the meaning of colonial nesting sites, which Student 24 believes it means that adults lose or miss some of their young.

A seeming lack of knowledge appears to be more common. Such a lack of knowledge is evidenced in, (a) students commenting that they do not understand a Given, (b) students commenting that they do know something about a particular animal, and (c) students not relating to or manipulating information in a Given. Students commenting about specific information that they are not familiar with is an obvious indication of a lack of knowledge, but occurs infrequently. Not paying attention to Given information occurs much more frequently.

Another aspect of knowledge use involves the uncertainty with which specific information is used. A Given is considered "used" if it is repeated or manipulated in any beyond the initial reading of the Given statement. The mere repetition of a Given or some portion of it is not necessarily an indication of certainty on the part of the student. For example, Student 25 states an interpretative definition of "osmoregulatory" from the water Given of squid as "osmosis or something." Although such a statement was interpreted as being used, it clearly does not demonstrate an extensive understanding of the concept of osmoregulation.

The major conclusion that can be drawn from an analysis of student knowledge characteristics is that an elaborate conceptual understanding appears to have a positive effect on successful problem solving. Such a conceptual understanding can enhance a students' ability to remember Given information, or keep it accessible to WM. More meaningful understanding of the concepts involved also appears to provide a basis from which inferences can be made.

The way in which heuristics, strategies and student characteristics come together in the context of working specific problems comprises what be called solution paths. The product of solution paths is the construction of problem representations. Examining such solution paths and problem representations can offer some insight into the strengths and weaknesses of student problem solving efforts. In addition, some of the errors that students make can be demonstrated quite clearly. On example of a solution path and its concomitant problem representation will be examined next.

Solution Paths and Problem Representations

In the present study, several factors are included in the design of solution path flowcharts: (a) the effect of accurately and inaccurately used information, (b) the use and effect of specific strategies, (c) the depth of processing of information, and (d) the types of information generated from Givens (see figure 2). The fundamental characteristic of the flowchart design discriminates between the accurate (left-hand side) and the inaccurate (right-hand side) use of information (see figure 2). Whether or not information is used accurately is determined by the amount and content of information available to the student (what Givens have been accessed at that particular point).

The structure of the flowchart delineates four levels of information usage: (a) inferring (inf), (b) interpreting and defining (int), (c) using complete (C) Given statements, and (d) using incomplete (I) Given statements. The levels proceed from greater to shallower depth of processing, respectively. In the flowchart, the depth of processing is represented by columns in a grid that extend from the outer vertical edges inward (from greater to shallower depth of processing). The last design characteristic sequentially segments the protocol according to the Givens accessed. Each Given segment is designated by a horizontal line that extends all the way across the figure. Within each segment on the outer edges are letters representing the specific Given accessed in that segment of the protocol (F = food, A = air, W = water, R = reproduction, P = protection, and E = ecology or behavior). A circle around the letter designates the Given which is accessed in that particular segment.

Key to Figure 2

* = occurrence of encoded item (repetition, inference, interpretation, etc.)
[#] = number in brackets indicates place in protocol sequence
(-) = indicates negative test (rejection)
→ = arrow pointing away from item is test against against item at end of arrow
— = connector (between items repeated in sequence or between item and description

(status icon)	= status comment	inf	= inference	niche	= to a niche
(focusing icon)	= focusing comment	int	= interpretation	hab	= habitat
c	= complete (Given)	def	= definition	func	= function
i	= incomplete (Given)	str	= to a structure	beh	= behavior
cnj	= conjecture	ecol-pos	= ecological position	proc	= process
sol	= solution	sup-cat	= superordinate category		

Clue Categories:

F = Food	A = Air	W = Water
R = Reproduction	P = Protection	E = Ecology/Behavior

Shaded area in box containing the category letter indicates the Given accessed by the student in that segment of the trial.

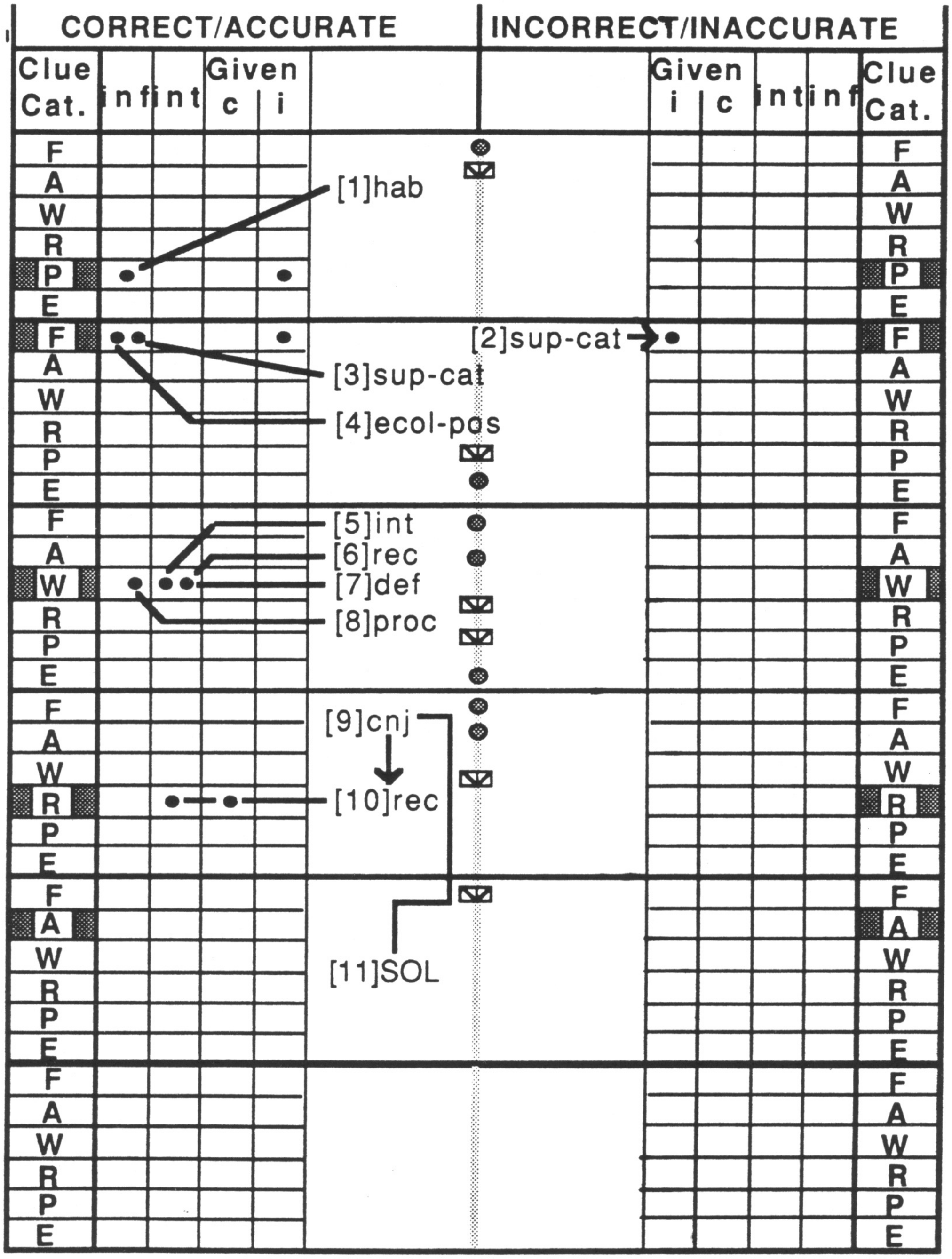

Figure 2 . Solution path flowchart for Student 24, jellyfish problem.

The inferential elaborative approach in the solution paths of Student 24 is characterized by the manipulation of information within most of the Given segments. During the first three segments of the jellyfish problem (figure 2), the student generated a number of inferences and interpreted or defined several Givens. During the fourth segment, she produced the correct conjecture. She tested the validity of the conjecture against information she recalled from reading she had done in her childhood.. During the next segment, she decided to enter the conjecture as a solution (see transcript segment in table 5).

One might expect, from the extensive use of inferences, that the resulting problem representation would appear more elaborate. However, the representation of "jellyfish" (see figure 3) only includes information related to two of the five Givens accessed. The depiction of the protection Given was modified by the addition of two inferences (habitat and superordinate category). The representation of the reproduction Given was supported by her recall of knowledge. Although her solution path involved the manipulation of information related to the other Givens, the results did not appear to directly influence the problem representation. In the retrospective reporting session, she could not remember the food, air, and water Givens. The key to her solution was the association of the reproduction Given to prior knowledge. The inferences and interpretations that did not appear in the actual problem representation may have contributed to the direction and focus of her thinking, but not to the point of being directly involved in the construction of the problem representation. In other words, the results of productive thinking may not end up being included in the problem representation, but may contribute the the direction of the solution path.

Table 5

Selected portions of the transcript of Student 24, problem 3.

PROTECTION CLUE: translucent to transparent body
3. translucent to transparent body
4. hmm
5. has to something in the water

FOOD CLUE: digestion begins in gastric cavity and is completed in food vacuoles of cells in radial canal system
15. I don't know if higher organs have food vacuoles
16. I think it's lower
18. low on the food chain
19. does that make sense

WATER CLUE: limited osmoregulation - are usually considered to be osmoconformers
34. conforms to the environment
35. hmm
36. probably since I just learned this
37. and osmosis means that
38. regulates the water within and without
39. so
40. it probably regulates its own particular pressure of water

REPRODUCTION CLUE: reproduce both sexually and asexuallv within each life cycle
49. I think I know what it is
50. it's got to be a jellyfish cause I had
51. I had a little biology book when I was little
52. and I remember this was really weird (...) jellyfish can reproduce
53. both sexually and asexually

The major characteristics of Student 10's solution paths prevent him from making accurate inferences and conjectures. The objects upon which his strategies focus do not produce accurate results. Although his supposed to keep information active in WM, he tended to focus only on the Given which was presently being repeated or most recently seen. For example, in the squid problem he generated (a) a "frog" conjecture based on "tongue," (b) a "fish" inference based on "gills," and (c) a "bird" inference (and solution) based on "highly developed eyes and...complex behavior." By primarily focusing on only one Given, the student was not able to develop an elaborate problem representation that adequately defined the animal in question.

The primary characteristics of Student 14's solution paths are (a) minimal manipulation of information through repetitions and inferences, (b) recall of only individual components of selected Givens, and (c) a tendency to generate high typicality conjectures first. She commented on having difficulty remembering the Givens. As a result, by consistently incorporating only portions of Givens, she constructed problem representation that lacked clarity, as well as an elaborate richness.

The solution paths of Student 25 are characterized by shallower levels of thinking and information manipulation throughout most segments. The major difficulties she encountered include (a) not keeping complete Given information accessible, (b) not referring to other Givens, and (c) lacking a continuity of reasoning or direction throughout the solution path. The first two difficulties involving the accessibility of Given information are readily apparent from the solution paths and problem representations. The difficulty, however, is more subtle. She maintained the continuity of two conjectures over two or more segments, but she did not maintain the continuity of Given or interpreted information.. In a way, the continuity problem seems to be the underlying cause of the first two difficulties. Essentially, she lacked any strategy for keeping information accessible: (a) little or no repetition of information and (b) little or no inferring. Her overall focus appeared to be on generating "the" answer and focusing only on conjectures. Her focus for searching memory centered on two pieces of information that acted as the stimulus. As she said in one retrospective session, I was "just trying to think of the sea and [what] they eat." After making that statement, she commented, "that wasn't very clear." Indeed, the basis of her focusing strategy was vague, as was the overall quality of the solution path and problem representations.

Key to Figure 3

F = Food Given
- 1a = digestion [begins]
- 1b = in gastric cavity
  [and is completed in]
- 2a = food vacuoles
- 2b = of cells
- 2c = in radial canal system

A = Air Given
- 1a = dissolved oxygen
- 1b = is absorbed directly by
- 1c = cells

W = Water Given
- 1a = osmoregulation
- 1b = cellular
- 1c = limited
- 2 = osmo-conformers
  [are usually considered to be]

R = Reproduction Given
- 1a = reproduce [both]
- 1b = sexually [and]
- 1c = asexually
- 1d = within each life cycle

P = Protection Given
- 1a = body
- 1b = translucent [to]
- 1c = body

E = Ecology/Behavior Given
- 1b = non-pursuing
- 1a = carnivores
- 2a = that are only sensitive to
- 2b = light
- 2c =touch
- 2d = chemicals [and]
- 2e = balance

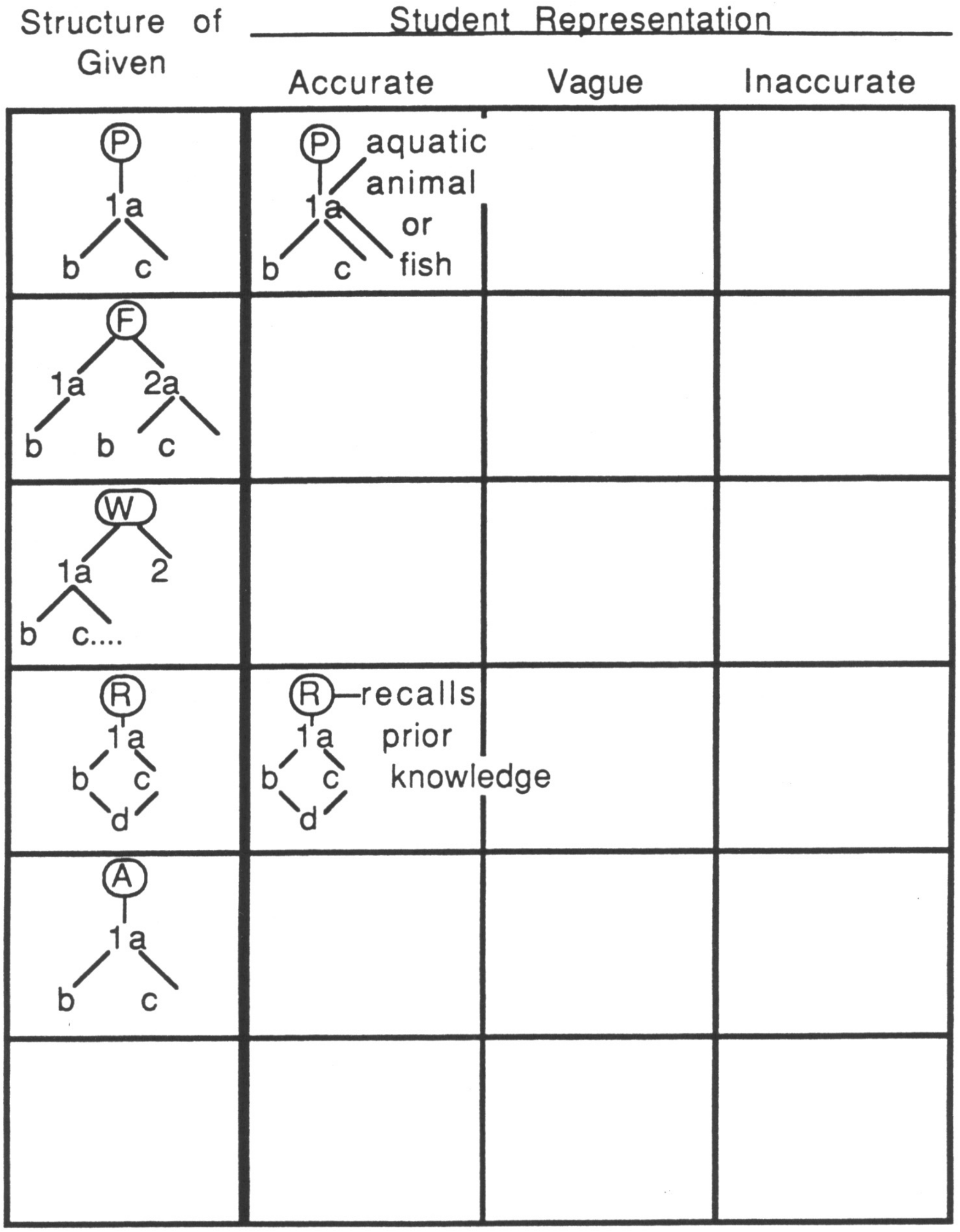

Figure 3. Student 24's problem representation of jeffmfish problem (jellyfish conjecture).

Heuristics

Four major heuristics were evident among the students who participated in the problem solving tasks. The first set of heuristics involved the students' approach to searching memory for associations to the information provided in the Givens: (a) random search and (b) focused search. The second set involved the strategic approaches used in attempting to solve the problems: (a) trial-and-error, (b) generate-and-test, and(c) inferential elaboration (see table 6).

The strongest of the five heuristics were, (a) inferential elaboration, (b) generate-and-test, and (c) focused search. All three approaches often appeared in the same problem solving sequence. In general, these three heuristics appear to be associated with a more well-organized knowledge-base. In support of the level of organizations the fact that inferences are usually made without a great deal of effort. The student sees the Given in the clue statement, may or may not hesitate or repeat the Given, and then states the inference. Focusing searches appear to involve the repetition of information that is, at least, somewhat familiar to the student. The testing of conjectures requires familiarity with the life history of the animal put forth as a conjecture, so that its characteristics can be matched with the information in the Givens and inferences.

Table 6

Heuristic and their characteristics

Heuristic		Characteristic
Search Approaches		
1. Random Search	a.	Lack of specific guidelines.
	b.	Possible solution to problem as goal.
2. Focused Search	a.	Specific information from Givens and/or inferences used as guidelines
Strategic Approaches		
1. Trial-and-Error	a.	Generation of conjectures with little reference to more than one Given and/or inference.
	b.	Decision to enter or not enter conjecture as solution is not well-defined.
2. Generate-and-Test	a.	Generation of conjectures reference more than one Given and/or inference.
	b.	Decision to enter conjecture is based on test against Givens and/or inferences.
3. Inferential Elaboration	a.	Generation of inferences from Givens.
	b.	Inferences provide elaborate problem representation.

Discussion

The students' approaches to solving the biological identification problems used in the present study involved a number of common patterns and demonstrated a number of factors that appeared to influence successful performance. The heuristics, strategies, and several solution path characteristics (the sequential and overall frequency of information manipulation, construction of problem representations, etc.) represent the major patterns employed by the students. The most significant factors affecting successful problem solving appear to involve the extent and elaboration of conceptual knowledge and the quality of and extent to which information is manipulated.

Based on an analysis of the data, a model of problem solving have been formulated (see figure 4). Although the role of decision-making was discussed earlier, the extent to which students make decisions was not explicitly apparent from the data. However, students must be making decisions at some level. Such decisions, at the very least include the following: (a) what Given and retrieved (from LTM) information to include (or focus upon) in the problem representation, (b) what information to use as a focus for searching memory, (c) what information to repeat, (d) what information to compare in terms of tests of validity, (e) what information to ignore, and (f) what conjectures or superordinate category inferences to enter as solutions. Decision-making appears in the figure as "D-M" at the following locations: (a) focusing, (b) repeating, (c) testing of validity, (d) retrieving, and (e) entering a solution. It is highly probable that the control of the decision-making process is rooted at the evaluative or metacognitive level. Evidence of activity at the metacognitive level appears to involve student comments that were encoded as status comments (including student's view of self and, in some instances, focusing comments. Since most information is filtered through the metacognitive and decision-making processes, such processes appear as the central component of the model.

The model also includes several components that relate to the processing of information from the task environment and problem representation. The processing components include the following: (a) "focusing" of attention on memory searches and problem representations, (b) "searching" of memory, (c) "inferring" (and other types of associating), (d) retrieving ("retrieval" of) information from memory, (e) "testing the validity" of conjectures against Givens or other information and of inferences against Givens, and (f) "repeating" information from the task environment or problem representation. Other components of the models include, (a) task environment Givens, (b) episodic LTM (personal experiences), (c) semantic LTM (factual and conceptual knowledge), (d) problem representation containing information retrieved from LTM, task environment Givens, conjectures, and the solution.

The difficulty with any model is the presentation of a static quality. In actuality, the model presented in figure 4 is a framework for a dynamic process of information manipulation. The problem representations undergo a process of constant change. New information is included while other information is forgotten. The strategies and heuristics discussed previously describe the patterns of activity or information manipulation. Once again, such patterns of activity seem to be controlled by the problem solver at the metacognitive level of decision-making.

Specifically, the model of problem solving that describes the approach of Student 24 (most successful problem solver) appears in figure 4. The major pathways are indicated by the. wider arrow lines and describe the strategies used more frequently by the student. The overall pattern of these dominant strategies comprise the heuristics characteristic of Student 24's approach to solving the problems. In the figure, task environment Givens are frequently focused upon immediately and used in a search of memory. Of particular significance in her searching of memory is the extensive use of both episodic and semantic stores. During these searches of memory she frequently makes inferences which are retrieved and incorporated in the problem representation. The line extending directly from semantic LTM to retrieval, in the figure, indicates the retrieving of conjectures and simple interpretative statements. Her emphasis on developing the problem representation with inferred information is indicated by the thick line extending from "retrieval" to "information from LTM" in the problem representation. The thick lines extending from "inferring" to "retrieval" and on to "information from LTM" characterizes her use of the inferential elaboration heuristic, the focus of which is on developing elaborate problem representations.

Information retrieved from LTM and Givens from the task environment are both used as focuses for searching memory (indicated by the thick lines extending past "focusing" and on to "searching"). Such information and Givens are also used through repetition as a way of focusing on searching memory (indicated by the thin lines extending to "repeating" and from "repeating" past "focusing"). The number of thick lines passing by "focusing" is indicative of her use of the focused search heuristic. In addition, Student 24 also makes extensive use of testing the validity of both conjectures and information retrieved from LTM. In the figure, such testing is shown as heavy lines from "conjectures" to "information from LTM" and "Givens from task environment." The information retrieved from LTM is also tested against the Givens (indicated by the heavy lines extending to "testing of validity" and from "testing" to "Givens"). The large number of thick lines extending to and from "testing" is characteristic of her use of the the generate-and-test heuristic. Her effectiveness at reaching solutions is indicated by the thick line extending from "conjectures" to "solution."

Although the flow of information is, to a large extent controlled by decisions, many of these decisions seem to occur automatically and are not readily apparent to the problem solver or researcher. However, some decisions and the effects of other decisions have been described from the protocols. The aspects of the inferred model of problem solving that lead to effective problem solving include, (a) inferring from

Given information, (b) interpreting Givens, (c) recalling past experiences, (d) comparing pieces of information for testing the validity of inferences and conjectures, and (e) using several propositions as a focus for searching memory.

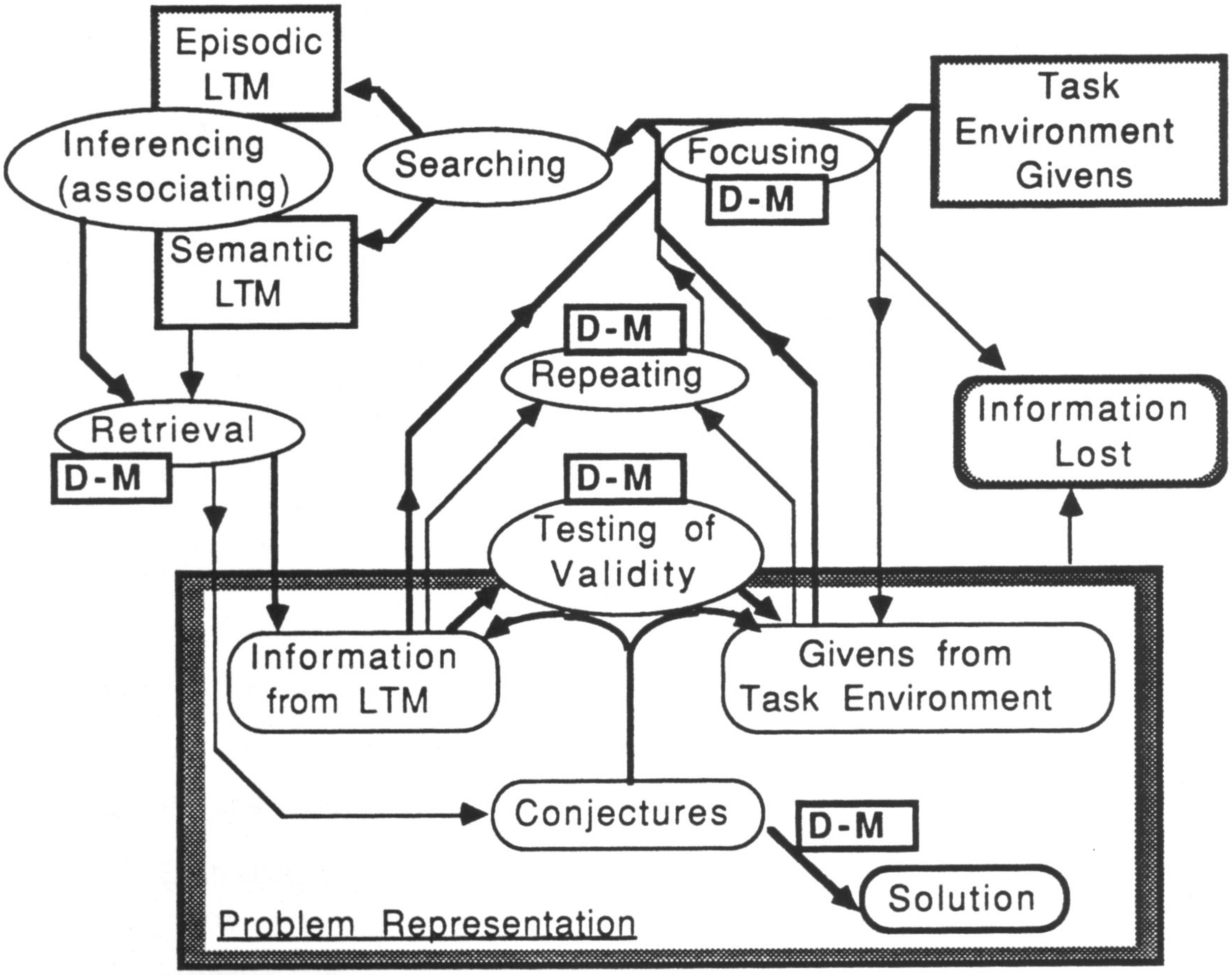

Figure 4. Model of problem solving derived from the protocols of Student 24 (D-M stands for decision-making).

The decision-making noted in the previous models appears to play a significant role in determining the way in which information is manipulated. The results of the decision-making process can influence whether the problem solving endeavor is successful or not. In order to better understand the difficulties encountered in solving of the problems presented in the study, Table 7 outlines the areas of difficulty which negatively influenced effective problem solving. These areas of difficulty are grouped into several categories. Although one category is referred to as "decision-making," one must keep in mind that all of the items listed are influenced by student decisions.

In general, many of the decisions involving information manipulation are influenced by the characteristics of the particular individual's prior knowledge. Decisions to include or ignore Givens or other information in the problem representation or as a focus of search appear to involve the existence and/or strength of associations with relevant information in memory. If such associations are lacking, then inclusion of Given information in the problem representation is not likely.

Table 7

Summary of areas of difficulty In solving problems.

Relating to Givens

Some meaningful or relevant Givens are not included in problem representation.
Some meaningful or relevant components of Givens are not included in problem representation.

Information Manipulation

Information in Givens is misinterpreted.
Information in Givens, when introduced, is not manipulated.
Not enough information manipulation takes place.
Information is not kept active or accessible.

Focus of Memory Searching

Focus only on Given being repeated.
Focus only on Given most recently seen.
Focus only on one or two Givens.
Focus on components of Givens.
Focus on erroneous inferences and interpretations.

Knowledge Characteristics

Limited knowledge of subject matter that is related to the information in the Given.
Conceptual understanding is lacking or not very elaborate.

Decision-making

Rejected inferences and conjectures are accepted.
Validity of inferences and conjectures is not tested.

Overall Approach

Finding "the" answer is the primary focus, rather than elaborating and developing the problem representation.
Maintaining a focus on a conjecture, rather than maintaining a focus on Givens and other generated information.
Solution path lacks a continuity of reasoning and focus.

Decisions involving the overall approach are influenced by prior knowledge, as well as a student’s view of himself and the subject matter. In fact, if a student has a weak knowledge structure of the subject matter, he or she is likely to have view of self as inadequate. Even if the student has a relatively strong background in the subject matter, the way in which others (teachers, fellow students, parents, etc.) view that student's ability can result in a similar view of self. Essentially, the metacognitive realm of decision-making can be influenced by a large number of variables, which have not been specifically considered in the present study.

The model presented in this paper has been formulated in an attempt to elucidate the relationships and patterns among the various strategies, heuristics, and memory structures. Other researchers have conducted similar studies of problem solving, but none of them have depicted models in the same way. Much of this research in the past ten years has used information processing as a paradigm. Information processing psychology, however, is based on computer modeling. One way in which researchers, such as Stewart (1983) in science education, have represented models of problem solving has been in the form of flowcharts, which are characterized as linear representations with dichotomous (yes-no) decisions. Such models are easily adapted to developing computer programs that can imitate particular problem solving processes. However, flowcharts fail to describe the dynamic and potentially parallel processes that occur with individual students. The models suggested in the present study, however, allow for concurrent processing and provide a context for the changing, fluid nature of problem representations.

Other researchers coming from a background of information processing, such as Larkin (1980; et al.,1980), have concentrated on the role of student knowledge structure in their models of problem solving. Specifically, Larkin has analyzed the node-link relationships or propositional structures of problem representations. Such representations are useful in studying the specific knowledge structures developed by students while solving well-structured problems. The models developed by Larkin are similar to propositional representations, but are much more elaborate. The processes used in the construction of node-link models are not included.

However, Larkin (1984) presents a descriptive model of problem solving in chemistry. The model is based on how students construct problem representations of chemical conversion problems. The problem representations in the molar conversion problems are defined as the strategies used in reaching solutions. For example, the three most common strategies described in her study have to do with the way students represented the Given information: (a) as group representations that assemble or separate groups of Givens according to size and use common operations among all examples, (b) as group representations that apply two steps of different common operations, and (c) as the inferring of relations that are then converted into common operations (two step process). The model presented by Larkin describes in detail how individual students process a specific set of well-structured problems. In contrast, the present study involves tasks that are not well-structured and require the use of a number of strategies in order to formulate problem representations and ultimately correct solutions.

From the results of the present study, the way in which students represent knowledge does not appear to be reflective of the knowledge structure of the science disciplines. What students do represent are a combination of their own personal interpretations of what they have studied and what they have experienced. With more abstract concepts such as osmosis and osmoregulation, students have had little direct experience of such phenomenon in their everyday lives. As a result, not one of the four students had extensive or elaborate knowledge structures of osmosis. On the other hand, more concrete phenomena that students can conceivably experience in their everyday lives are more elaborately structured in their memories. For example, the students in the present study tended to make more inferences about the concepts of food acquisition and protective behaviors and structures. Evidence of such concepts are more easily observable in pets and in neighborhood and zoo animals. Is the facilitation of conceptual learning due, in part, to the extent of prior personal experiences?

As discussed by Rosch et al. (1976) and Anderson (1983), the strength of the connection between information is based on how essential such information is to the meaning of the concept. However, even if certain abstract information is essential to the meaning of a particular concept, such knowledge may be difficult to understand because of the lack of prior knowledge and the difficulty with which such information can be manipulated. In addition, Anderson's (1983) contention that the increased strength of accessibility of information occurs from an elaboration upon conceptual knowledge through an automatic inferential process. Such a contention is supported by the apparent ability of Student 24 to make inferences in the context of information retrieval. If inferential productions (automatic processes) are used in the construction of knowledge, would they also be present in the utilization of such knowledge in the context of problem tasks?

The way in which students categorize animals has some intriguing implications. The one student who listed atypical examples of animals on the word association task was a much more successful problem solver. She made more inferences than any of the other students. Can a categorization scheme containing a wide variety of exemplars be indicative of a more extensive and elaborate organization of memory? If such is the case, then as Sokal (1974) and Bruner et al. (1956) contend, an extensive classification system in memory can have the following effects: (a) allow memory to work more economically, (b) information can be retrieved more easily, (c) information can be manipulated more easily, and (d) conceptual structures and relationships can be better represented in memory.

If we expect students to construct an extensive and elaborate understanding of biological concepts, then three aspects need to be considered. First, can the way in which students categorize information in memory be assessed by the teacher during instruction? The categorization schemes that students have constructed from their personal experiences could be brought into the context of classroom instruction. Second, can the approach to teaching conceptual material start from or include a classification scheme? If, as Bruner et al. (1956) contend, classification is essential to the organization of meaningful knowledge, then the teaching of biology can employ an approach that structures knowledge according to one or more classification schema. For instance, the classification of animals could be presented by drawing out student conceptions of animal categorization. The characteristics and relationships of such conceptual categories can then be explored. At the same time, the relationships inherent in a scientific classification scheme can be explored and compared to the students' conceptions. Problems that a-rise out of conflicting conceptions can initiate further inquiry into the nature and validity of those concepts. Third, should students be exposed to as many experiences as possible with the phenomena contained within specific concepts? Where students have prior knowledge of such concepts, instruction could address that knowledge while introducing the scientific version of the concepts.

As discussed previously, the existence of classification schemes for animals can allow for the ease of retrieval and manipulation of information. The case of Student 24 (atypical exemplars) provides an interesting example of how such a classification scheme can affect problem solving performance. In constructing problem representations, she made many associations (inferences) with information in memory. Such associations represent the retrieval and, in many cases, the manipulation of information (deeper level inferences). Additional manipulation was facilitated by her ability to keep information accessible. The making of inferences appears to be associated with the process of "chunking". By tapping into a conceptual scheme, such as inferring that an animal is low on the food chain, an extensive amount of information is made available. For example, an animal, such as a house fly, that occupies a position low on the food chain has a number of structural (e.g., mouth in the shape of a suction cup) , behavioral (e.g., taxic responses), and ecological characteristics (e.g., larvae and adults contribute to decomposition processes). All such information can potentially be made available through that particular associative pathway.

Although not discussed previously, the role of metacognitive control of working memory functions became apparent from the analysis of the protocols. A number of researchers have discussed metacognition, but Sternberg (1984) most aptly described what he calls meta-components as the processes that are used in developing and governing the use of strategies. Other researchers have included metacognitive processes in what is referred to an executive memory (Taylor & Evans, 1985) or in working memory itself (Atkinson & Shiffrin, 1971). In whatever position metacognitive processes occupy, their existence certainly appears to play a significant role in the processing of information in working memory. As discussed in the conclusions section, students are constantly making decisions about, (a) the state of the problem solving process, (b) what information to focus on, (c) what information to ignore or dismiss, (d) what strategies to use for keeping information accessible or active, and (e) what information to include in the problem representation. Essentially, such decisions control the flow of information in WM. Atkinson and Shiffrin (1971) consider the control of information flow to be under the control of WM. Is such control actually associated to some extent with a more objective or metacognitive locus? Unfortunately, contrary to Atkinson and Shiffrin's contention that WM is under conscious control, including the decision-making process, students do not seem to be aware of such decision-making processes. They may vocalize decision statements, however the use of the decision-making process does not appear to be determined by any kind of strategic plan. Although one student (Student 10, high grades) planned to look at certain Givens in order to get certain kinds of information, his decisions in other instances following no such pattern.

The metacognitive component appears to be influenced by affective characteristics of the individual. The student who remarked several times that she felt "so stupid" was not performing as well as she may have been capable. In a way, such a view of oneself interferes with the clarity needed to make decisions. Does a student's preoccupation with self image interfere with his or her ability to view the problem solving process objectively?

A major implication of the role of metacognitive decision-making for teaching can be to place more focus on involving students in observing and analyzing their own metacognitive processes. Can a description of metacognitive processes and how they work be discussed with students directly? In the context of individual and group discussions, analytical and evaluative questions and decisions could be brought to the forefront. As discussed previously, presenting students with alternative classification schemes can be used to invoke such analytical and evaluative questions about the value and coherency of each classification system. Focusing on such decision-making processes appears to be the central issue in the development of critical thinking ability. As Munby (1982) contends, the development of critical thinking should be at the forefront of every educator's mind.

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