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ABSTRACT

Characteristics of successful and unsuccessful problem solvers in categorization tasks are examined in this study of undergraduate students. Findings are reviewed of the categorization and solution tasks undertaken by a group (N=21) of science majors at a private university. The subjects were classified as either successful or unsuccessful in their efforts as problem solvers with classical genetics tasks. It was found that having a mental framework for categorizing problems according to similarities in the way they can be solved contributed to problem-solving success. It was suggested that successful genetics probelm solving involves not only the ability to recognize the genetics concept underlying the problem, but also the ability to recognize the appropriate approach to solving the problem. Detailed tables summarize the data from the study. (ML)

CATEGORIZATIONS OF CLASSICAL GENETICS PROBLEMS BY SUCCESSFUL AND UNSUCCESSFUL PROBLEM SOLVERS

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Introduction

In recent years several studies have suggested that when experts approach a problem they often begin by categorizing it, i.e., recognizing it as one of a given type of problem (c.f. Hinsley, Hayes, & Simon, 1977). This recognition is hypothesized to "activate a general schema stored in long term memory, which includes a set of appropriate approaches for solving this type of problem (Chi, Feltovitch, & Glaser, 1981). Intuitively, and according to the self reports of experts, the use of categorization would appear to be a strategy which is vitally important to problem-solving success in the sciences. This position is supported by research such as that of Silver (1979) who found that within a sample of eighth graders the tendency to sort verbal math problems on the basis of mathematical structure was significantly positively related to problem-solving performance scores. Chi and others (1981) observed that novices categorize physics problems according to the "surface structure" of the problem while experts sort according to "deep structure"-- the underlying physics law applicable to the problem. Surprisingly, these researchers also found that their experts attended to the same (if fewer) keywords in the problems. Similarly, Weiser and Shertz (1983) found that the manner in which computer programmers sorted a group of programming problems varied according to their expertise, with novices sorting according to the problem's "more literal features," experts according to "algorithm" (content-specific deep structure), and managers according to the "kinds of programmer to whom they would give each problem."

In many of these studies, researchers have typically drawn their subjects from a pool of novices and a pool of experts and compared the performances of the two. Research (e.g.,Smith & Good, 1984; P. Simmons, 1987 personal communication) has demonstrated that successful subjects generally share more characteristics which distinguish them from unsuccessful subjects than do experts when compared to novices. In the former study, a group of moderately successful novices who used powerful "expert-like" strategies while solving a group of moderately difficult genetics problems was identified and the argument was made that if an artificial dichotomization of the subjects was to be made, it should be based on problem-solving success instead of subject expertise.

Other researchers have also argued for research which contrasts successful and unsuccessful subjects so as to eliminate the variable of experience which confounds the expert/novice research findings (Bodner & McMillen, 1985). Together, these studies support the contention that certain expert problem-solving characteristics (such as automatic processing) may, in fact, be the <u>effect</u> of continued success (experience) and not the cause of problem-solving success. (It must be noted, however, that this approach is not appropriate when relatively simple, algorithmically solvable "problems" are being studied).

This paper details the findings of the second of three phases of a project which essentially seeks to replicate these studies using the successful/unsuccessful design in an attempt to:

a) corroborate the surface/deep structure conclusion which has become an essential component of our understanding of problem-solving,

b) examine more closely the nature of the categorization procedure and how it is applied,

c) reexamine the similarity of keywords identified by the subjects, and,

d) extend the research into another content area, enhancing the generalizability of the conclusions.

The procedures and findings of the pilot study and first phase of this project have been presented earlier (Smith, 1986). In a pilot study using personal interviews, ꟷ faculty geneticists each developed an organizational scheme for 28 classi etics problems. Based on this experience, 15 college and university faculty biologists from across the nation were also asked to organize these problems. In a preliminary report of five faculty responses, we observed the following:

1) biologist faculty members apparently had a detailed mental organizational structure for genetics problems;

2) genetics problems appeared to be organized mentally by these individuals in a hierarchical system;

3) the self-report of at least one subject suggests that this organization plays a significant role in problem solving;

4) the genetic principles used by faculty subjects to organize genetic problems appeared to be very similar in most cases;

5) the organizations produced were clearly based on "deep structure," i.e., genetic principles, and not on more "surface features";

6) the keywords identified by the subject were very closely tied to the organizational scheme being used implying that the recognition of these keywords is an essential component of the process by which the problem is recognized as being typical of a class of similar

problems.

Methodology

Data collection. In the present study, a group of 21 student volunteers who were enrolled in an introductory biology course for science majors at a private, liberal arts university in the Southeast were asked to organize a group of typical genetics problems. These problems were those used in the previous phases of the study which had been drawn from a widely used undergraduate genetics text and included problems from most of the chapters on classical genetics.

Students were first asked to sign a consent form and to complete a participant profile sheet. These data are summarized in Table 1. Next, students were each given a set of the 28 problems in 3" X 5" index cards. The problem sets had been numbered and arranged into sets by random order. The subjects were asked to "organize the problems based on how you would solve them. . . . in any way that makes sense to you" and then to "circle the keyword(s) in each problem, that is, the words which are important in the organization decisions you make." Students noted the time they began the sorting and the time they finished.

Upon completion, students were asked to "briefly describe your organization on a sheet of paper", to "give each label you use and the ID numbers of the problems you associate with each." Students were encouraged to give a "brief (one sentence) description of what each of your labels means."

After this task was completed, the subjects were asked to solve a set of four moderately difficult problems which had been found useful in earlier phases of the study and in earlier studies (Smith & Good, 1984) for meaningfully categorizing subjects as either successful or unsuccessful problem solvers. Approximately one to one and one half hours were required to complete the categorization and solution tasks. The data obtained from these subjects was combined with that of seven faculty volunteers, five of which have been described previously (Smith, 1986).

Scoring of problem solutions. The subjects' solutions to each of the four problems were evaluated by the investigators using two different methods. The first method (Smith & Good, 1984) identified each solution as correct--Y, essentially correct--(Y), or incorrect--N. As in our previous research, subjects who produced a correct (or essentially correct) solution to at least one of the four problems were identified as successful subjects. Those individuals who failed to produce at least one correct solution were considered to be unsuccessful subjects.

In order to calculate Pearson correlation coefficients, each problem solution was assigned a point value on a scale of one to five. The scoring scheme for each problem was unique to the problem. For example, in one of the problems involving a single gene with a lethal allele, the solver was asked to determine ratios in a second generation derived from a heterozygous parental cross. In this problem, one point was given for each of the following: obtaining the correct F1, obtaining all possible F1 x F1 combinations, properly balancing the relative proportions of F2 genotypes, correctly summarizing the results of the F2 crosses, and noting lethality. Similar scoring schemes were developed for the other three problems and are available from the authors.

Categorization Schemes. Each subject's categorization scheme and the corresponding set of problem cards were evaluated by the two investigators. The schemes consisted of category labels, the numbers of the problems belonging to that category, and (usually) a brief description of each category.

Each category in a scheme was rated according to the apparent depth of processing used to form the category. The ratings were as follows:

Superficial: some feature of the problem as it is stated or given in the problem is used to form the category.
e.g., problems in which a pedigree is involved grouped under the heading "Pedigree".
e.g., problems about "corn" grouped together.

Deep: A genetics concept not specifically mentioned in the problem is used to form a category.
e.g., Problems involving a single gene grouped under the heading "Monohybrid Crosses".

Superficial/Deep: Both an unstated genetics concept and a surface feature of the problem are used to form a category.
e.g., "Monohybrid cross, animals".

No Processing: Whimsical categories not meaningfully related to the content of the problems.
e.g., "Problems I would attempt", "other".

Categories rated as "superficial" were further classified into three subgroups according to whether the focus was on the information given in the problem ("Superficial Givens"), information requested in the problem ("Superficial Requests"), or "Both".

Results and Conclusions

The two ratings of the problem-solving performance of each of the subjects are presented in Tables 3 and 4. As we have reported previously, subjects find these problems to be moderately difficult ($\overline{X}$ p.s. score= 55%). This is especially true for student subjects ($\overline{X}$ = 49%) but also for faculty ($\overline{X}$ = 75%). As expected, the performance of the mostly pre-med student subjects in the present study was better than the performances of the less well prepared students in previous studies.

Next, successful and unsuccessful subjects were compared according to "depth rating", i.e., the percentage of categories produced by each subject which were judged to represent deep concepts (Table 5). A depth rating for each categorization scheme was calculated as follows:

$$\text{depth rating} = \frac{\text{\# of deep categories} + 1/2\ (\text{number of superficial/deep categories})}{\text{total number of categories}}$$

Successful subjects had a mean depth rating approximately six times that of the unsuccessful subjects (44.0% vs 7.3%, Table 5). Furthermore, successful subjects used categories judged as strictly deep in our scheme more than eight times as frequently as did the unsuccessful subjects (42% vs 5%). Successful subjects are therefore more likely than unsuccessful subjects to use categories evidencing a knowledge of genetic principles.

In the terms of formal logic, the use of deep categorization is neither a "necessary" nor a "sufficient" condition to problem-solving success, however. Some individuals (e.g. S19) who produced categorization schemes which received low depth ratings (0%) were moderately successful problem solvers (p.s. score=65%). On the other hand, some individuals such as F12 who produced categorization schemes which received relatively high depth ratings (86%) were less successful problem solvers (p.s. score = 50%). One of the reasons why the use of deep categorization schemes is not sufficient to insure problem-solving success is that using deeper categories is a separate phenomenon from appropriately categorizing problems within those categories. Several subjects (e.g. S22) used some deep categories but included within these categories problems which were inappropriate to that grouping. The value of using appropriate category labels is in recognizing that a common approach can be used in solving problems belonging to that group. If the problem solver does not correctly recognize members of the group, his/her mental representation of the problem type with its associated solution approach is of little or no value, contributing to the decreased success noted in these individuals in the present study.

Successful problem solvers frequently used both superficial and deep categories, with only three successful subjects in this study using deep categories exclusively. Certain of these superficial categories are appropriate in genetics problem solving. A "pedigree problem", for example, may involve any one of several genetics concepts (mono-or dihybrid crosses, sex-linkage, etc.), even though a single strategy of hypothesizing and testing patterns of until a best fit is found is appropriate for the solution of most pedigree problems. The category "pedigree" may therefore signal a type of problem-solving approach in addition to being a superficial feature of the problem.

Comparisons of the depth ratings for faculty vs student subjects were also drawn (Table 5). Although the faculty use a greater percentage of deep categories [$\overline{X}$ depth rating = 75.1% (faculty); 19.6% (students), there were several students judged to be successful by our scheme and a few (e.g. S08, S20, and S22) who were remarkably successful, having scores greater than the faculty mean. The latter individuals tended to have higher depth ratings, i.e. the depth of their categorizations more closely resembled that of successful faculty than the categorizations of their unsuccessful peers. This conclusion is further supported by the strength of the positive correlation observed between problem solving scores and depth ratings of the students (r=.36; Table 5). For this very limited sample of students, therefore, the depth rating alone accounts for 12% of the variance.

In summary, the depth of the categories used is positively correlated with problem solving success (r=.36 for all subjects) and the wisdom of using the successful/unsuccessful distinction to categorize subjects into groups which are meaningful in other dimensions of problem solving is again supported.

Four examples of categorization schemes produced by subjects demonstrate differences in the depth of the category labels used. The labels used (Figure 1) by subject F11, for example, read much like the table of contents in a genetics text ("monohybrid", "dihybrid", "Dominant/Recessive", " Multiple Allele", etc.), while several of the category labels used by subjects S26 and S07 (Figures 2 and 3) focus on superficial problem components such as the organism involved ("humans", "Drosophila", "corn"). These two categorization schemes also demonstrate the difference between categories which focus on problem "givens" (S26) and problem "requests". The scheme of subject S07 (with a depth rating of 0%) is also presented in order to emphasize that some schemes which may appear to represent knowledge of deep genetic principles do not require such processing. The terms used by this subject as category labels are indeed genetic concepts, but the word itself is invariably present and circled as a keyword on each of the identified problem cards. Subject S22 (Figure 4) represents an intermediate between the two extremes, using some deep category labels ("simple dominance") and some superficial categories ("known results - what were parental generation?"). In addition, subject S22 is typical of those individuals who use category labels which have both superficial and deep aspects.

The use of such hybrid categories by several individuals merits special attention. For example, subject S22 produced some large categories evidencing deep concepts - "simple dominance" and "sex linkage". These categories were subdivided, however, into categories based on superficial criteria, e.g. "questions regarding possible outcomes of crossings". The use of such hybrid categories demonstrates that using deep categories is not an "all or none" phenomenon. Further research is needed to document how the transition from using mostly superficial categories to using a greater proportion of deep categories occurs and how this transition can be encouraged.

Implications for teaching

The results of the present research have several implications for classroom teaching in general, and for genetics instruction in particular. First of all, having a mental framework for categorizing problems according to similarities in the way they can be solved contributes to problem-solving success. It would therefore appear to be appropriate for instructors to emphasize the value of such organization and the planning which is implied. Assigning problems to appropriate categories, however, is a separate skill which also contributes to problem-solving success. Practice with specific feedback should be provided for both activities.

One of the most important teaching goals for instructors in courses such as genetics which include a large problem-solving component must be helping students learn to recognize what is important. For genetics this is sometimes a superficial component of the problem. but is more often the recognition of the deeper genetic principle involved. The "weak heuristics" (e.g., means/ends analysis) are rather effective problem-solving approaches across many domains-both in formal education and in daily life. Successful genetics problem solving, however, involves developing an additional group of more powerful ("content specific") heuristics based on an understanding of the genetic principles involved in the problem. Encouraging the transition to the use of these more powerful heuristics is likely to require much attention and patience since the weaker heuristics have been so useful so the individual in the past.

Successful genetics problem solving involves not only the ability to recognize the genetics concept underlying the problem, but also the ability to recognize the appropriate approach to solving the problem. One approach, described above for pedigree problems, requires a process of hypothesis formulation and testing. Other types of genetics problems have characteristic processes associated with their solution as well. The most common type of genetics problem might be called "given the parent, determine the offspring". In order to solve these problems, students must be able to correctly assign genotypes, form gametes, and predict the outcome of the crosses - usually with a Punnett square. Another problem type appears superficially to be the opposite of the type just described: "given the offspring, determine the parents". Skills required for solving problems of this type, however are quite different from those required to solve problems of the other type. Here, students need to know how to calculate Mendelian ratios from the data given and the significance of these ratios, i.e., the inheritance patterns that led to these ratios. Instruction which places a greater emphasis on such problem-solving processes would likely lead to greater student success at applying these processes, resulting in increased problem-solving success.

These recommendations remain to be tested in the classroom to determine whether or not they enhance problem-solving performance.

Table 1: Subject characteristics: Students

Subject #	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Age	20	20	19	19	21	19	19	19	21	39	19	20	20	20	19	19	20	19	21	20	19
Sex	F	F	M	M	M	F	M	F	F	F	F	F	M	M	M	M	F	F	M	F	F
High School Biology ?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Genetics in H.S. Biology?	N	Y	N	N	N	Y	N	Y	Y	Y	N	N	Y	Y	Y	Y	Y	N	Y	Y	Y
College Year	3	3	2	3	3	2	3	2	4	5	2	3	3	3	3	2	2	3	3	3	3
College Major	Bio	Nut	Chem Psy	Econ	-	Psy	Chem, Bio	Und	Physic Philos	Eng	Chem, Music	Eng	Bio	Chem	Relig, Liber. Studies	Bio	Bio	Chem	Hist	Psy	Bio
# College Bio Courses Completed	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	-	1	2	1
Grade	C	-	A	-	-	C	A	-	A	-	A	-	A	A	A-	B,A	B,A	-	-	-	-

Table 2: Subject characteristics: Faculty

Subject #	Terminal degree: degree	Terminal degree: Institution	Terminal degree: area	Terminal degree: year	Semester Hours of Graduate Genetics	Years of College Teaching	Teaches: Intro.Bio.	Teaches: Genetics	Teaches: Genetics Related	Academic Title	Current Institution	Sex	Age
F01	M.S.	NWS-L.A.	Cytogenetics	72	3	6	X		X	Asst.	J.C.	F	40
F02	Ph.D.	Tulane	Biology	67	0	19	X	X	X	Assoc/Chair	College	M	44
F08	Ph.D.	S.Dakota State	Entomology	70	-	20	X			Instr.	Univ.	M	-
F09	Ph.D.	U.of Ga.	Botany	72	6	16	X			Assoc.	J.C.	F	47
F11	Ph.D.	U. of Cincinnati	Aquatic Ecology	72	3	14	X		X	Prof.	College	M	43
F12	Ph.D.	Cornell	Entomology	75	4	6	X			Assoc.	Univer.	M	37
F13	Ph.D.	Ohio St.	Genetics	68		20		X		Prof.	Univer.	F	48
F30	Ph.D.	Cornell	Science Ed.	82	0	6	X			Asst.	Univer.	F	35

Table 3: Problem Solving Success of Subjects

Subject #	Problem Number 1	2	3	4
Students:				
S06	N	N	N	N
S07	N	N	N	N
S08	N	N	(Y)	Y
S09	N	N	N	N
S10	N	(Y)	(Y)	N
S11	N	N	N	N
S12	N	N	N	Y
S13	N	N	N	Y
S14	(Y)	N	Y	Y
S15	N	N	(Y)	N
S16	N	N	N	Y
S17	N	N	N	N
S18	N	N	N	Y
S19	N	N	Y	Y
S20	N	Y	(Y)	Y
S21	N	N	N	Y
S22	N	N	N	Y
S23	N	N	N	N
S24	N	N	(Y)	Y
S25	N	N	N	N
S26	N	N	N	N
Faculty:				
F02	(Y)	(Y)	(Y)	Y
F08	Y	Y	Y	Y
F09	(Y)	N	(Y)	Y
F11	N	N	(Y)	(Y)
F12	N	N	N	Y
F13	Y	Y	N	Y
F30	N	Y	N	Y

TABLE 4: Problem Solving Success Scores. (Subjects dichotomized by relative success)

Subject #	Problem # 1	2	3	4	Total P.S. Score (%)
Unsuccessfuls:					
S06	0	0	0	0	0 (0)
S07	1	0	1	0	2 (10)
S09	1	0	2	0	3 (15)
S11	2	1	2	0	5 (25)
S17	3	0	2	0	5 (25)
S23	2	1	2	1	6 (30)
S25	2	0	2	0	4 (20)
S26	2	1	2	0	5 (25)
$\overline{X}$=	1.6	0.4	1.6	0.1	3.75 (19)
Successfuls:					
S08	4	2	4	5	15 (75)
S10	4	2	4	3	13 (65)
S12	3	2	1	5	11 (55)
S13	3	0	3	5	11 (55)
S14	5	3	5	5	18 (90)
S15	3	0	4	0	7 (35)
S16	4	3	3	5	15 (75)
S18	4	3	2	5	14 (70)
S19	0	3	5	5	13 (65)
S20	4	5	3	5	17 (85)
S21	3	1	3	5	12 (60)
S22	4	3	4	5	16 (80)
S24	4	1	2	5	12 (60)
F02	4	3	1	4	12 (60)
F08	5	5	5	5	20(100)
F09	4	2	4	5	17 (85)
F11	3	2	4	5	14 (70)
F12	3	0	2	5	10 (50)
F13	5	5	1	4	16 (80)
F30	4	5	1	5	15 (75)
$\overline{X}$=	3.7	2.5	3.1	4.6	13.9 (70)
All Students: $\overline{X}$ =	2.8	1.5	2.7	2.8	9.7 (49)
All Faculty: $\overline{X}$ =	4.0	3.1	2.7	4.7	14.9 (75)

Table 5: Depth Ratings of Subject Categories by Depth of Representation Implied. (Subjects dichotomized by relative success)

Subject #	Superficial Requested's	Superficial Given's	Superficial Both	Superficial Deep	Deep	No Processing	Depth Rating (%)	P.S. Score(%)
Unsuccessfuls								
S06	2	3	1	0	0	0	0	10
S07	4	3	0	0	0	0	0	15
S09	3	2	0	0	0	0	0	25
S11	5	2	0	0	0	0	0	25
S17	0	0	0	0	0	2	0	30
S23	0	1	1	3	2	0	50	20
S25	4	0	0	0	0	0	0	25
S26	0	5	0	1	0	0	8	19
% of Total	41	36	5	10	5	5		
X̄ =							7.3	45
Successfuls								
S08	2	1	3	1	1	0	19	75
S10	0	0	1	0	5	0	83	65
S12	0	4	2	0	0	0	0	55
S13	9	1	0	0	0	0	0	55
S14	3	2	0	2	0	1	13	90
S15	0	1	0	1	3	0	70	35
S16	2	1	0	3	0	0	25	75
S18	0	1	1	1	2	0	50	70
S19	4	0	0	0	0	0	0	65
S20	0	0	0	1	2	1	63	85
S21	4	4	0	1	0	0	6	60
S22	5	1	0	6	0	0	25	80
S24	5	0	0	0	0	0	0	60
F02	0	2	0	0	6	0	75	60
F08	1	1	0	1	5	0	69	100
F09	0	3	0	0	10	0	77	85
F11	0	0	0	0	13	0	100	70
F12	1	0	0	0	6	0	86	50
F13	1	1	0	0	1	0	33	80
F30	0	1	0	1	9	0	86	75
% of Total	25	16	5	12	42	1		
X̄ =							44	70
All Students:								
% of Total	39	24	7	15	11	3		
X̄ =							19.6	49
All Faculty:								
% of Total	5	13	0	5	79	0		
X̄ =							75.1	75
All Subjects:								
% of Total	27	20	0	11	35	0		
X̄ =							33.5	55.5

Figure 1: Categorization scheme used by Subject F11
14 Years of College Teaching
Ph.D.: Aquatic Ecology
Successful (Problem Solving score = 70%)
Depth Rating = 100%

Monohybrid; Dom/Rec

Trihybrid; Dom/Rec

Monohybrid; Multiple Allele

Monohybrid; Inc. Dominance

Monohybrid; Sex-Linked

Dihybrid; Lethal

Dihybrid;Multiple Allele/Dom-Rec

Monohybrid; Lethal

Pedigree

Dihybrid; Dom/Rec

Dihybrid; Multiple Allele

Differentiating Between Types of Crosses

Dihybrid; Linkage

Figure 2: Categorization scheme used by Subject S26
Junior, Biology Major
Unsuccessful (Problem Solving score = 25%)
Depth Rating = 8%

Humans

Drosophilia

Unsuccessful Crosses

Cross between 2 different animals

Dominance on alleles over recessive

Corn outer appearance

Figure 3: Categorization scheme used by Subject S07
Junior, Nutrition Major
Unsuccessful (Problem Solving score = 10%)
Depth Rating = 0%

Probability

Pedigree

Recombination Frequency

F1 and F2

Genotype

Phenotype

Crosses

Figure 4: Categorization scheme used by Subject S22
Sophomore, Biology Major
Successful (Problem Solving score = 80%)
Depth Rating = 25%

Simple Dominance, Known Results

Sex Linkage, Questionable Outcomes

Sex Linkage, Known Results

Percentage of Recombination

Probability Questions; Gamete,Zygote Outcome

Probability Questions; Sex Linked

Probability Questions; Pedigree

Determining Genetic Pattern of Inheritance Using Pedigrees

Determining Genetic Pattern of Inheritance Using results of Offspring

Proportions Expectations; Simple Dominance

Proportions Expectations; Sex Linked

Proportions Expectations; other

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