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ABSTRACT

Nine undergraduate science and non-science majors (novices) who had recently completed their first college classroom study of genetics and seven genetics graduate students and biology instructors (experts) were videotaped as they attempted to solve a selected group of seven moderately complex classifical genetics problems and three Piagetian tasks (proportions, probability, and combinations). Three conclusions based on the analysis of the videotape recordings appear to be warranted. First, for the three schemas studied, formal thought is not a condition "sufficient" to determine success in dealing with portions of genetics problems which require applying that scheme. Second, for the formal schema of combinations at least, formal operational thought does not appear to be a necessary condition to success in solving genetics problems of the type presented in this study. Third, while not addressing the question directly, results are in agreement with previous research which suggests a positive correlation between cognitive development and success in genetic problem-solving. The paper notes that it is premature to assume that concrete operational students should not study classical genetics. (JN)

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IS FORMAL THOUGHT REQUIRED FOR SOLVING CLASSICAL GENETICS PROBLEMS

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IS FORMAL THOUGHT REQUIRED FOR SOLVING CLASSICAL GENETICS PROBLEMS?

Perhaps the largest body of literature in science education is that which deals with the work of Jean Piaget and its implications for science educators. One of the most rapidly expanding areas of science education research, on the other hand, is the study of problem-solving performance. Few attempts have been made to relate these two areas of study. This paper is one in a series which report on a larger, naturalistic study [illegible] to identify and compare successful and unsuccessful problem-[illegible]g strategies as well as the relationships between these and cogn[illegible]ve development.

One issue on which the work of Piaget has had considerable impact is that of the appropriate point at which various topics should be introduced into the student's education. Considerable effort has been expended to analyze the cognitive demands of various courses so as to align their introduction with the students' cognitive development (e.g., Glass, 1981). One of the more logical points at which to begin our analysis of Piagetian theory and problem solving would be to consider the role of cognitive development in school subjects such as genetics which require a quantitative approach to problem solving. The topic of classical genetics has r[illegible]eived little research attention in this respect but has been assumed to require formal operational abilities.

Few studies have addressed the validity of that assumption. In a study of 14 ninth-grade biology students, Stewart (1982) observed that the students' lack of understanding of meiosis appeared to be the principal difficulty in explaining their solutions to a group of simple genetics problems. Stewart suggested that this difficulty was strictly related to the subject's understanding of genetics and not to any inability to generate combinations. Considering that the subjects were high school freshmen and that no data were presented to support this contention, further study of this issue seems necessary. In a more recent study of 27 high school students, Stewart (Note 1) drew similar conclusions, adding that the "inability of these subjects to generate gametes . . . did not stem from an inability to follow combin[illegible]torial rules: since when "given a rule for generating three-letter combinations from . . . six letters," most could follow the rule. It should be pointed out, however, that such algorithmic applic[illegible]ion of a rule would not be considered a generally acceptable assessment of the status of the formal operational schema of combinatorial logic.

In an earlier related study, Emery (1973) studied the effect of an individualized genetics instructional unit on the development of the probability and combinatorial schemas in a group of 90 high school biology students. She found that the instruction had essentially no effect on cognitive development.

At the college level, Moll and Allen (Note 2) found difficulties with student understanding of meiosis as did Stewart, but no assessments of cognitive development were made. In contrast to Stewart's findings, however, studies by Walker, Hendrix, and Mertens (1979) demonstrated that the level of Piagetian development was positively correlated with success in solving Mendelian genetics problems. Correlation coefficients ranged from .36 to .21 over the Piagetian tasks administered. In related research, positive correlations have also been observed between performance on Piagetian tasks and scores on verbal mathematics problems (Bellile, 1980), achievement in a physics course (Bawman, 1976), and performance on Algebra I problems (Grady, 1975).

The study which has most directly addressed the relationship between cognitive development and genetics problem solving is the dissertation study of Gipson (1984) in which 150 general college biology students who had just completed a Mendelian genetics unit performed Piagetian tasks in the areas of proportions, combinations, and probability, and correlations were sought between the level of cognitive development for each schema and performance on genetics problems deemed to require each type of reasoning. (Note that this research was performed after that being reported here.) The Pearson correlations computed were considered to be "not high" (.33 to .49) while correlations representing combined reasoning types, i.e., general level of cognitive development were "consistently higher." On the basis of these findings, Gipson concluded, "We can s · with a high degree of certainty that formal thought is necessary for solving Mendelian genetics problems, but we do not know enough about formal-operational thought to relate its characteristics directly to what we perceive to be the specific reasoning type necessary in solving genetics problems." While the second half of this assertion appears to be supported by his data, the necessity of formal operational thought has not been evidenced. A correlation between the two parameters has been supported but a causal relationship has not. This is a particularly important issue because this data led Gipson to conclude that genetics instruction is "little place" in the middle-school or high-school classroom" since these non-formal students are "not capable" of understanding the "formal concepts seen in Mendelian problems." Further, he suggests that "those who teach introductory courses in biology on the college level . . . [should make] sure that genetics problems are studied as late in the course as possible . . ."

These rather dramatic recommendations, along with the research review before, demand that we carefully consider several questions: (a) Is formal operational thought a sufficient condition to successful genetics problem solving?; (b) Is it a necessary condition?; (c) Does it augment problem-solving success?; (d) Are the underlying principles of Mendelian genetics formal (as Gipson also maintains)?; and e) If so, what specific formal reasoning abilities are required? The answers to these questions should be valuable both theoretically and practically. Theoretically, they would add to our meager understanding of the intersection of cognitive developmental and problem-solving theories; practically, they should help educators to make more informed decisions about the appropriateness of genetics instruction at various levels.

While the statistical correlation between cognitive development and genetics problem-solving success is addressed by the psychometric research cited above, questions of necessity and sufficiency suggest a case study experimental design. As a part of an ongoing naturalistic study, videotapes of 17 subjects solving genetics problems and performing Piagetian tasks were available for this case study analysis.

(Analyses of the successful/unsuccessful strategies observed in this study have appeared elsewhere: Smith, 1983; Smith & Good, 1984).

Methodology

In this study, nine undergraduate science and non-science majors (novices) who had recently completed their first college classroom study of genetics and seven genetics graduate students and biology instructors (experts) were video-taped as they attempted to solve a selected group of seven moderately complex classical genetics problems and three Piagetian tasks. The genetics problems were selected from a pool of several hundred problems collected from published and unpublished sources. Problems were chosen to span a range of complexity and content and to reflect common pedagogical emphasis. The selected problems are characterized in detail in Table 1.

The Piagetian tasks selected were the "Frog Problem" (proportions) developed by Lawson (Note 3) and the colored shapes (probability) and the switch box (combinations), as used by Lawson (1978). Tasks for assessing these particular schemas were selected not only because these abilities logically seemed to be involved in solving many genetics problems, but also because of Stewart's contention (Note 1) that student difficulties in genetics are not related to the lack of combinatorial ability in contrast to the positive correlations observed by Walker, et.al. (1979) on these schemas.

Subjects were selected by theoretical sampling (Bogdan & Taylor, 1975) to provide maximum variability for age, sex, college major, genetics training, and performance in genetics courses. The general interview technique was modeled after the "think-aloud" protocols of Simon, Larkin, and Lochhead and the clinical procedures of Piaget. In this interview, the subject is encouraged to think aloud and is interrupted as little as possible. Standardized protocols were used in the Piagetian portion of the interview following the general procedures of Piaget. Each interview required approximately 90 minutes.

Following this data collection, the video-tape records of the interviews were studied extensively. The genetics problem solutions were scored for common problem-solving patterns. Videotapes of the Piagetian interviews were then scored according to established standards (Sills & Herron, 1976; Piaget & Inhelder, 1951/75; and Note 3). Any task which did not lead to a straight-forward categorization was reviewed by a second expert and a consensus of opinion was reached.

Results

The problem-solving success and the Piagetian performance of each subject are presented in Tables 2 and 3. It can be seen from Table 2 that the genetics problems were at least moderately difficult, since even the experts (especially E06, E07, and E10) were unable to achieve satisfactory solutions to several of the problems. As synthesized in Table 4, these data show that the more formal subjects tended to be more successful at solving the genetics problems presented. Given that the majority of the successful subjects were experts, however, the problem-solving success may be the result of their expertise and not their cognitive development. Although this question cannot be answered conclusively by the data collected here, the results are at least in keeping with the expected tendency of formal subjects to be more successful at problem solving.

Next, a careful review of the problem-solving protocols clearly demonstrates that being able to perform at the formal operational level on the probability task, for example, does not ensure that the subject will be successful in dealing with a portion of a problem that requires applying probabilistic concepts. Numerous examples of this phenomenon were identified for all three schemas studied. Thus, at least for these three schemas, formal operational thought is not sufficient to determine problem-solving success.

On the other hand, subjects judged non-formal for a schema do indeed often have greater difficulty than formal subjects with problems requiring that kind of thought. This is perhaps most evident of the schema of probability; subjects such as N03, N05, and even E07 (judged non-formal on the probability task) experienced considerable difficulty with the probability portions of the given problems--problems 1A, 1B, an/or 4. (See Table 1.)

Finally, given that formal operational thought is not a sufficient condition but is likely a condition conducive to genetics problem-solving success, is it a necessary condition? That is, could instances be identified in which the subject clearly performed non-formally on a given task and yet was able to successfully deal with a portion of some problem apparently involving the related schema?

Careful study of the subject videotapes revealed instances for all three of the schemas studied. Regarding the schema of proportions, two expert subjects (E03 and E10) were judged non-formal on the "Frog Problem" and yet were successful in dealing with proportions in the genetics problems. Considerable evidence exists in the transcripts of at least one subject, however, this may be a false negative. Although chosen for its lack of content-ladenness, the "Frog Problem" may, in fact, be highly content-laden for persons trained in biology. They may see the problem as a poorly designed experiment and be unable to focus on solving only the ratio and proportion aspect of the task. This appears to be the case for E10 who expressed concern over not knowing "what kind of rigor he [the experimenter] used to collect, how extensively he collected, how big the pond was," etc. Given that both E03 and E10 were expert subjects to which this caveat might apply, the observations made here cannot be considered sound evidence for the necessity or lack of necessity of formal operational thought for handling proportionality in genetics problems.

Also, regarding the schema of probability, the possibility that the Piagetian assessment of subject N09 is a false negative must be considered. On this task (the colored shapes), the subject performed acceptably in every respect except for not taking into account the lack of replacement which alters one fraction used in the last portion of the task. It is conceivable that instead of evidencing the lack of the formal operational schema, however, the omission of this operation may have been the result of the subject's not paying appropriate attention to the task. (This was the last task in the rather lengthy interview). This possibility is further supported by the subject's earlier adept handling of probability in such difficult problems as Problem 4. (As is the case for most genetics problems, however, none of the problems presented in this study involved the formal operational skill of determining the probability of consecutive events without replacement.) Thus it seems unwise to accept the performance of this subject as acceptable evidence of the lack of necessity of formal operational thought for handling probability in genetic problems.

The performance of subject N06 regarding the schema of combinations cannot be so easily put aside. The sequence of combinations which she attempted (shown in Appendix A) shows an organized system for identifying all possible 1-switch and 2-switch combinations. Beginning with her 3-switch combination, however, she became agitated and confused. Her subsequent attempts do not appear well organized so that she, in fact, missed two of the possible 3-switch combinations. While her performance is superior to the random attempts of certain other subjects, this subject must be judged concrete operational for this schema. In Problem 3, however, N06 did find all nine possible different combinations of the genes involved. It must also be noted that this genetics problem is analogous to the combinations task, both requiring the combination of four different positions with two different options at each position. (There are only nine different genotypic combinations, however, since Bb is the genetic equivalent of bB, for example.)

This subject's performance raises the distinct likelihood that the formal operational schema of combinations is not a necessary condition to identifying all possible combinations in a genetics problem. The apparent logical contradiction is more comprehensible upon a more detailed, case-study analysis of N06's solution of Problem 3. First, the subject drew the three possible pair-wise combinations at each gene (BB, Bb, bb and CC, Cc, cc), noting the probability of each, considering the two genes separately. Then she began to draw the possible combinations of the six pairwise combinations, multiplying to obtain the appropriate probabilities. After drawing probabilities for five of the possible nine, she stopped to add the calculated probabilities. Seeing that the probabilities did not sum to 1.0, she continued searching for combinations, apparently until the corresponding probabilities did indeed sum to 1.0 Checking to see that the calculated probabilities sum to 1.0 is a strategy (to be discussed later) commonly used only by the more successful subjects and is clearly the aid which allowed this concrete operational subject to properly identify all possible combinations. Therefore, at least in problems of this level of complexity to which this strategy can be applied, and for subjects who can and do apply it properly, the formal schema of combinations may not be a necessary condition to identifying all possible genetic combinations.

Discussion

From the data obtained in this study, three conclusions appear to be warranted:

First, for the three schemas studied, formal thought is not a condition sufficient to determine success in dealing with portions of genetics problems which require applying that schema. This also seems intuitively correct, since having a certain ability would not appear to guarantee successfully performing the related task upon demand; anxiety, motivation, and related solver-specific variables would likely come into play. That is, a subject may--for any number of reasons--not perform at the level of which he is competent. This has been recognized and discussed at length by several authors as inherent in the measurement of any competency by the related performance. (See for example Yost, Siegel, & Andrews, 1962; Siegel & Brainerd, 1978; and Wollman, 1978.) On the other hand, the subject may be performing to his/her potential but has not yet learned to apply his understanding within the context of genetics problems, i.e., to transfer his understanding to this domain. Therefore, formal operational ability alone is insufficient to achieve problem-solving success.

Secondly, for the formal schema of combinations at least, formal operational thought does not appear to be a necessary condition to success in solving genetics problems of the type presented in this study. Some subjects are apparently able to solve such problems by appropriately applying the knowledge that the sum of all probabilities is 1.0 check which they seem to have learned to be a useful tool in genetics problem solving.

Thirdly, while not addressing the question directly, the results of this study are in agreement with previous research (Stewart, 1982; Note 1; Note 2) suggesting a positive correlation between cognitive development and genetics problem-solving success.

Whenever asking questions about necessity and sufficiency, the most serious limitation is the possibility of false positives or negatives in any Piagetian research. The former are simply subjects who have not yet reached a given cognitive level but are erroneously judged to have those competencies. Conversely, false negatives involve subjects who have attained a given cognitive level but do not perform at that level and thus are judged to be below it. In this study, the possibility of false positives was largely eliminated by selecting Piagetian tasks and genetics problems which were sufficiently difficult so that they could not be solved algorithmically. False negatives in the Piagetian data, however, do constitute a difficulty which must be reckoned with, since they can be a direct result of the lack of congruence between competence and performance--a difficulty inherent in Piagetian research as previously noted. While the false negative argument may apply to subjects E03 and E10 for the "Frog Problem," the weight of the evidence suggests that this is not the case with subject N06 for the switch box (combinations) task. The ability of this subject to identify a complex series of all possible combinations in a genetics problem by using her knowledge of the sum of probabilities should be viewed as an example of the lack of necessity of the formal schema of combinations for solving combinatorial genetics problems.

This suggests that even though no similar solid examples for the schemas of proportions and probability were found in this limited sample, further sampling might identify such subjects. This is also suggested by a further analysis of the demands of most genetics problems in these two areas. Regarding probability, for example, typical classical genetics problems do not require determining the probability of sequential events without replacement. This is precisely the distinction Piaget and Inhelder (1951/75) make between concrete and formal individuals. The former can quantify probabilities but do not consider the lack of replacement. It is, therefore, possible to conceive of concrete operational subjects who can correctly solve typical genetics problems involving probability (with replacement). As to the schema of proportions, it appears that typical genetics problems require a level of performance considerably below that of setting up an equation comparing two ratios, such as is required in the frog task. None of these hypotheses implies that cognitive development does not augment genetic problem-solving success, or that other formal operational abilities are not required for genetics problem solving at this level. The formal operational individual's ability to deal with the abstract, for example, should be considered. In addition, unsuccessful subjects were observed to be more likely than successful subjects to make illogical statements and to fail to recognize a logical necessity, suggesting that the ability to use logic (including nonstandard logic systems) should be investigated.

Implications and Recommendations for Further Research

The findings of this study suggest reconsidering the assumption that solving classical genetics problems at the level of difficulty of those used in this study requires formal operational thought. Results show that certain subjects judged concrete operational for the schema of combinations are capable of solving the combinatorial portions of genetics problems. Logical arguments have also been made opposing the <u>necessity</u> of the formal schemas of probability and proportions. If some formal operations are required, then we must to other schemata as likely candidates. The previously mentioned research (Stewart, 1982) which shows the lack of understanding of meiosis, suggests that an ability to deal with the abstract may be a more important factor in the lack of genetics problem-solving success. Although a non-formal subject may be able to generate all possible combinations of gene symbols in a dihybrid cross (by using the sum of probabilities heuristic), s/he may not be able to determine which combinations are disallowed (by meiotic disjunction) during meiosis. For example, from the parental genotype AaBb, the subject may draw a gamete containing both A and a (a combination disallowed by Mendel's law of segregation) or gametes containing only one symbol (A alone, B alone, etc.) which are also disallowed. The combination of a pair of alleles (A and a) into a single gamete and the partitioning of two pairs of alleles into four types of 1-gene gametes are prevalent errors in unsuccessful dihybrid protocols. Careful analysis of such protocols suggests that these subjects are attempting merely to reproduce some pattern they have seen before or to produce "all possible combinations"; they either do not have a well-integrated knowledge of the meiotic process being symbolized or they fail to transfer that (abstract) knowledge to the problem solution.

Further study of problem-solving protocols regarding the use of such tools as the check of the sum of probabilities to determining whether or not all possible combinations have been identified, should be valuable. Are there other, similar checks? How are they used? How are they acquired? Does the subject use them in other domains? Such research is similarly called for by a prescriptive model for problem solving in physics recently proposed by Reif (Note 4).

Although this study has primarily addressed the cognitive demands of classical genetics problems and was not designed to empirically test the effectiveness of teaching the topic to various audiences, at least two pedagogical implications appear to be logical outgrowths of this project. First, based on the research data available to date, it is premature to assume that concrete operational students should not study classical genetics. Further research is required before that question can be answered with more confidence. While previous theoretical reservations about the appropriateness of genetics for concrete operational students have not led to the general omission of genetics from the high school curriculum, it has become common practice, both at the high school and the freshman college levels, to omit the probabilistic components of genetics from biology courses, arguing that the many concrete operational students in these classes cannot understand these concepts. Even in genetics courses where probability is addressed, instructors often use this argument to explain the lack of student success with these problems. Based on the results of this study and the even more convincing argument that few classical genetics problems require determining the probability of sequential events without replacement (the formal probability schema), it should now be clear that we can no longer use a cognitive development argument to excuse poor student performance on genetics problems involving probability, and that we should carefully reexamine the issue of whether or not to include probability as a basic component of our genetics courses.

Secondly, the observation of a number of subjects who perform at the formal operational level on a given task but apparently do not transfer that ability to relevant genetics problems, suggests that improved performance on genetics problems may be achieved by an instructional program which encourages students to recognize the logical equivalency of the structure of the genetics problems and their current understanding; to recognize, for example, that drawing all possible combinations of parental alleles into appropriate gametes is logically equivalent to determining all possible combinations of the same number of light switches or coin tosses. Given that our concrete operational students should be able to deal with these concrete examples and given that formal probabilistic concepts do not appear to be required for solving these problems, this approach seems reasonable. While many instructors already make reference to such analogies, more emphasis should be placed here. Just how these analogies should be used (e.g., students tossing coins, lecture/discussion of the analogies) so as to enhance this transferance is a question requiring further research.

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Table 1

Characterization of the Selected Genetics Problems

Problem No.	No. of Loci	Type of Inheritance	Pedigree Given?	Probability Involved?	Heterogametic Females Involved?	Solution Requested: Parental Genotypes	Solution Requested: Offspring Genotypes & Frequencies	Solution Requested: Mechanism of Inheritance
1A	1	simple dominance	No	Yes	No	No	Yes	No
1B	0	-	No	Yes	No	No	No	No
2	1	co-dominance/ recessive lethal	No	Yes	No	No	Yes	No
3	2	simple dominance	No	No	No	No	Yes	No
4	1	simple dominance	Yes	Yes	No	No	Yes	No
5	1	sex-linked autosomal	No	No	Yes	Yes	No	No
6	3	2 autosomal, 1 sex-linked	No	No	No	Yes	No	Yes

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Table 2

Problem-Solving Success of the Subjects

Subjects	Problem* 1A	1B	2	3	4	5	6	# Correct or Essentially Correct
NO3	N	N	N	N	N	N	I	0
NO4	N	N	N	N	N	N	N	0
NO5	N	N	N	N	N	Y	(Y)	2
NO6	N	N	(Y)	N	N	(Y)	I	2
NO7	N	N	N	N	N	N	N	0
NO8	N	N	N	N	N	N	I	0
NO9	N	N	N	N	(Y)	Y	X	2
N10	N	N	N	N	N	X	X	0
N11	N	N	N	N	N	N	I	0
E02	N	X	(Y)	(Y)	(Y)	Y	I	4
E03	N	Y	X	(Y)	Y	Y	(Y)	5
E04	N	Y	(Y)	(Y)	N	Y	(Y)	5
E05	N	N	Y	Y	Y	Y	(Y)	5
E06	N	N	Y	(Y)	I	X	(Y)	3
E07	N	N	N	N	N	Y	(Y)	2
E08	(Y)	X	(Y)	Y	Y	Y	I	5
E10	N	N	N	N	N	Y	(Y)	2

*Y=Yes, N=No, (Y) =Essentially Correct, X=Omitted, I=Interviewer halted work

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Table 3

Performance of the Subjects

on the Piagetian Tasks

Subject	Problem-Solving Success	Task: Proportions	Combinations	Probability
N03	0/7	NF	NF	NF
N04	0/7	F*	NF	F
N07	0/7	NF	NF	F
N08	0/7	F	F	F*
N10	0/7	F	F	F*
N11	0/7	NF	NF	NF
N05	2/7	NF	NF	NF
N06	2/7	(F)	NF	F*
N09	2/7	NF	F	NF
E10	2/7	NF	F	F
E06	3/7	F	F	F
E02	4/7	F	F	F
E03	5/7	NF	(F)	F*
E04	5/7	F	F	F
E05	5/7	F	F	F
E07	5/7	NF	NF	NF
E08	5/7	F	F	F

* Subject made minor error in computation, etc.

( ) Responses considered marginally acceptable

Table 4

Relative Problem-Solving Success of Subjects

Grouped by Piagetian Performance

Piagetian Performance[1]	Number of Subjects Correctly Solving 0 Problems	1-3 Problems	4-5 Problems
Nonformal	3	2	0
Transitional	2	3	1
Formal	1	1	4

[1]Nonformal=nonformal on all three tasks, Transitional=Formal on only one or two tasks, Formal=Formal on all three tasks

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Appendix A

Sequence of switch combinations attempted by subject N06 on the switchbox combinations task. (D=down, U=up)

Trail #	Switch # 1	2	3	4
1	D	D	D	D
2	D	D	D	U
3	D	D	U	D
4	D	U	D	D
5	U	D	D	D
6	U	U	D	D
7	D	U	U	D
8	D	D	U	U
9	U	D	U	D
10	U	D	D	U
11	D	U	D	U
12	D	U	U	D
13	U	U	U	D
14	U	U	D	U
15	U	U	D	D
16	U	D	D	D
17	D	U	D	D
18	U	U	U	U
19	U	U	U	D

20	U	D	D	D
21	D	D	D	U
22	D	D	D	D
23	U	D	D	U
24	D	D	D	D

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