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DEVELOPMENT OF A DIAGNOSTIC TEST TO DETECT MISCONCEPTIONS IN MENDELIAN GENETICS AND MEIOSIS

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(Technical Editor's Note: The authors supplied enlarged versions of several tables. These have been attached at the end of this paper.)

ABSTRACT

The diagnosis of previous knowledge and the exposition of misconceptions to estimate conceptual understanding is recognized as a need in science teaching. To meet this need a diagnostic test was designed using the methodology proposed by D. Treagust in 1987. The instrument assesses misconceptions in mendelian genetics and meiosis of non-major college biology students. It consists of 21 multiple-choice two-tier items, and is known as the Diagnostic Test of Mendelian Genetics and Meiosis. The test was administered to 197 students. The internal consistency coefficient (Cronbach alfa) was 0.61, and its stability coefficient 0.70. Item analysis revealed indexes of difficulty and discrimination of 0.39. Students' scores showed a positive and significant relation with reference to both student achievement in mathematics and the grades of the unit test offered by professors in charge of the courses. Thirty-two misconceptions were identified, some of them related to Puerto Rican and Latin American social beliefs. Based on the finding, recommendations for classroom instruction are presented.

INTRODUCTION

One of the areas of major interest for science education researchers, philosophers of science, cognitive psychologists and science teachers is the conceptual understanding before, during or after formal instruction in science. Many of the studies focus their attention on misconceptions -- those ideas and notions that students bring with them to science lessons and are inconsistent with those accepted by the scientific community. It is widely acknowledged that misconceptions are persistent (Pines & West, 1986) and difficult to change (Alvermann, Smith & Readence, 1985; Ausubel, 1986; Gabel & Enochs, 1987; Gómez, 1992; Hallown & Hestenes, 1985; Pines & West, 1986; Rice & Feher, 1987; Yarroch, 1985). When students manage new experiences and knowledge with incorrect information, misconceptions represent obstacles to learning (Champagne, Klopper & Gunstone, 1982).

Several techniques and methods are described in the literature for identifying misconceptions. The most widely used has been the clinical interview (Pfundt & Diut, 1991; Rowe & Holland, 1990; Wandersee & Mintzes, 1988). This method has the advantage of providing excellent information about student's misconceptions. However when the situation of the classroom teacher is considered, the interview has several limitations: it is time and labor intensive and thus difficult to apply to large numbers of students. It also requires substantial training. A methodology proven useful for the researcher may not be so for the classroom teacher.

Attempts have been made to use paper and pencil tests in order to collect data from more students that can be reached through the clinical interview. Various types of question formats have been used in such studies: true and false, open ended short essay, and multiple choice. The true and false variant was used by Ross and Shuell (1990) to detect misconceptions related to earthquake among primary school students. In the open ended short essay format Lawson and Thompson (1988) developed an instrument to detect conceptual understanding of genetics and natural selection. Other investigators including Tamir (1971) in the area of biology, Doran (1972) interested in elementary science, Linke and Venz (1978; 1979) in physical sciences, Halloun and Hestenes (1985) in mechanics and Trembath (1985), well known for his Trembath Test of Scientific Misconceptions, have used multiple choice tests to identify misconceptions. Wandersee (1983) in his Photosynthesis Concept Test added the requirement of justification for some of the items.

The approach used by Tamir (1971) is directly relevant to this study. He used the answers submitted by students to short and open ended questions as distractors for the multiple choice items. Also relevant is the particular methodology developed by Treagust (1987) for the explicit purpose of identifying misconceptions in specific content areas. In this procedure the construction of items follows a two-tier multiple choice format comparable to that of the Test of Logical Thinking (Tobin & Capie, 1981). The first tier consists of a multiple choice item and the second contains four possible reasons for the choice of the first tier. The students have a double task: first she or he has to choose the correct answer among the options of the first tier and then choose a justification to support the first choice. To date this methodology has been used to develop three diagnostic tests: one on covalent bonding (Peterson Treagust & Garnett, 1989), a second in photosynthesis and cellular respiration in plants (Haslam & Treagust, 1989), and the other on the solar system (Haslam & Smith, 1989).

The bibliographical index prepared by Pfundt and Duit (1991) reveals that although a considerable number of investigations have identified misconceptions in mendelian genetics

and meiosis, at college level there is no methodology for diagnosis that incorporates the explanations provided by the students. Due to its practical importance and social value, genetics is a permanent component of the college biology curriculum. It also offers opportunity for the valuable experience of problem solving. Among college biology professors in Puerto Rico the general consideration is that mendelian genetics and meiosis are topics of great difficulty for first year biology students. The purpose of this research was to design and validate a diagnostic test of a two-tier multiple choice format to identify misconceptions in mendelian genetics and meiosis. The study considered three aspects related to this purpose: the psicometric characteristics of the diagnostic test, the relation between the scores and the characteristics of the population under study and the most common misconceptions identified by the instrument.

METHODS

Subjects

The subjects of study were 197 students enrolled in the Biological Sciences course of the Biology Department at the Bayamón Technological University College of the University of Puerto Rico. They come from nine different faculties, 66% completed their high school in the public school system, and the proportion of females to males was 3 (75.6%) to 1 (24.4%). Their average high school achievement was 3.19 on a 4.00 scale (equivalent to B) while their college achievement fluctuates from 1.43 to 3.89 with an average of 2.16 (equivalent to C). The scores of the mathematic component of the College Admission Test was used as indicator of mathematic achievement. Only ten students surpass the limit established for not taking the remedial mathematic course. The results of an achievement test of mendelian genetics and meiosis offered by the professors was also considered to describe the subjects. The scores range from 12 to 47 from a maximum of 50 with an average of 31.31.

Instrument Development

Content delimitation

The conceptual structure of the content was specified by means of concept maps developed by one of the authors and validated by nine professors of the Biology Department at the Bayamón Technological University College and a specialist in genetics from the University of Puerto Rico in Río Piedras. As a result a list of propositions, relating two or more concepts of meiosis and mendelian genetics, was developed. The list was again subjected to the

validations of experts. The final list of propositions, presented in Table 1, delimited the content of the test.

To obtain information about students misconceptions several activities were done. First, the related literature dealing with misconceptions was thoroughly revised. Based on the information obtained and also on the experience of one of the authors as a college biology teacher, a list of misconceptions was prepared. The list was revised by professors of Biological Sciences of various campuses of the University of Puerto Rico to determine the generality of the misconceptions. Also, interviews with

TABLE 1

Propositions of Mendelian Genetics and Meiosis

Meiosis

1. Diploid organisms have pairs of homologous chromosomes.
2. Cellular and sexual reproduction require the duplication of DNA.
3. The sexual reproduction of diploid multicellular animals have gametogenesis as a requisite.
4. Gametogenesis includes cellular diferentiation and m,eiosis.
5. The duplication of DNA is a pre-requisite of meiosis.
6. The process of meiosis includes two nuclear divisions, such that the first is a prerequisite of the second.
7. The pairing of homologous chromosomes, synapsis, and the formation of tetrads are events that occur during the first meiotic division.
8. The formation of tetrads allows for recombination.
9. Independent assortment of chromosomes and segregation are events of the first meiotic division that follow the formation of tetrads.
10. The separation of sister chromatids and the formation of haploid nuclei occur during the second meiotic division.
11. As a result of meiosis the chromosome number of the gametes is haploid.
12. Gametes combines at random during fertilization to form zygotes.
13. With the formation of the zygote the diploid number of the species is restored.
14. Growth is the result of the cellular reproduction of the zygote.
15. Cellular reproduction includes mitosis and citocinesis.
16. Growth of the zygotes results in diploid multicellular animals

Mendelian Genetics

1. Mendelian genetics deals with diploid organisms that have a genotype and a phenotype.
2. The phenotypes are constituted by the traits of the members of the species.
3. The genotype is constituted by the pair of genes present in the individuals.
4. Alleles are the alternative forms or variants of a gene.
5. Each trait exhibited two variant: one dominant and one recessive.
6. Genes are related to alleles as traits are related to their variants or forms.
7. Alleles can be of two types: dominant or recessive. They are represented by big or small letters respectively.
8. The presence of the dominant allele mask the expresion of the recessive.
9. Alleles are present in pairs.
10. The pairs of alleles undergoes segregation and independent assortment during meiosis.

11. As a result of segregation and independent assortment gametes would have an allele of each pair in all possible combinations provided by the genotype.
12. For each trait there are three possible allelic combinations for the genotype: homozygous dominant, heterozygous and homozygous recessive.
13. The expression of the homozygous recessive genotype is recessive.
14. The genotypes homozygous dominant and heterozygous have a dominant expression.
15. If an individual of dominant phenotype is test cross, its genotype can be inferred.

Typology of problems

1. Problems in mendelian genetics can be classified in two types: Those that go from the causes (genotype of the parents is known) to the effects and those that go from the effects (phenotype and/or genotype of the progeny is known) to the causes.
2. If the genotypes of the parents are known the type of gametes and the proportions in which they should be form can be predicted considering segregation and independent assortment.
3. The Punnett square can be used to predict the variants and the phenotypic and genotypic proportions of the progeny. It is presumed that the union of gametes occurs at random.
4. If the phenotypes of the parents and the progeny of a cross are known the genotypes associated to each one of the traits can be determine.
5. To determine the genotypes, pair the phenotypes of the parents and the progeny with the six possible crosses for each one of traits.

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students that have completed the study of the topics under consideration were conducted to gain a broad perspective of their conceptual understanding. Multiple choice questions were written based on a limited number of propositions. Students answered them and also presented their reasons for selection.

Test construction

Items for the diagnostic test were based on the two-tier multiple choice format described by Treagust (1986; 1987) and comparable to Tobin and Capie design in their Test of Logical Thinking (Tobin & Capie, 1987). The first tier consist of content questions, the majority surpassing the recall knowledge level, with two to four choices. In the second tier the choices are five: one that is correct, three with identified misconceptions and a space where the students can write any other reason that is not presented. With this fifth alternative the teacher has the opportunity for more precise identification of conceptual understanding.

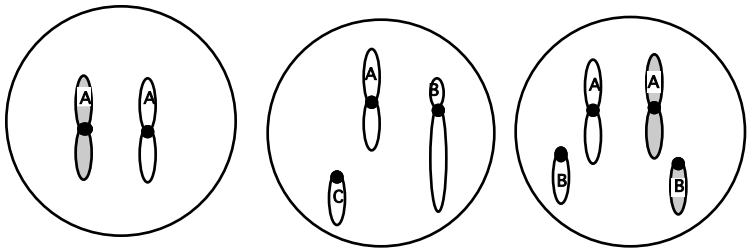
The two-tier multiple choice items were evaluated for format and style by two experts in test construction. To complement the study of content validity mentioned before another was done in which the test was administered to eight college students that had approved the Genetics course with A or B. The students (six females and two males) answered, discussed, and

evaluated the test considering instructions, content, time to answer and correct answers. The present form of the test consists of 21 questions: nine on meiosis and 12 on mendelian genetics and is known as the Diagnostic Test of Mendelian Genetics and Meiosis. An item testing the concept of haploid number (item number 6) is presented in Figure 1; an item related to the Punnett square (item number 16) is presented in Figure 2.

Figure 1. Item number 6.

WHICH OF THE FOLLOWING DIAGRAMS ILUSTRATES A CELL WITH AN HAPLOID NUMBER OF CHROMOSOMES?

a. b. c.



JUSTIFICATION FOR MY SELECTION:

The cell has:

1. one chromosome of each type.
2. one pair of homologous chromosomes.
3. two pairs of homologous chromosomes.
4. an uneven number of chromosomes.
5. _____

Figure 2. Item number 16.

A couple, both normal (**A**) for skin pigmentation have four children: two normal and two with albinism (**a**).

WHICH OF THE FOLLOWING PUNNETT SQUARES ILLUSTRATES THE PREVIOUS SITUATION?

a. (¡)**Aa** X **Aa**(™)

	A	a
A	AA	Aa
a	Aa	aa

c. (¡)**Aa** X **aa**(™)

	a	a
A	Aa	Aa
a	aa	aa

b. (¡)**AA** X **aa**(™)

	a	a
A	Aa	Aa
A	Aa	Aa

JUSTIFICATION FOR MY SELECTION:

1. The four children, two normal and two albinos are represented by each division of the square.

2. The four children, normal and albinos are possible variants in the progeny of heterozygous parents.

3. The children are all heterozygous, but in two of them albinism is dominant and in the other two normal is the dominant condition.

4. The parents of a cross are always homozygous and their children heterozygous.

5. _____

Most items of the diagnostic test are based on situations which requires surpassing the recall level of knowledge. Of the 36 propositions previously content validated, a limited numbers are tested. A specification grid is presented in Table 2 that relates the test items with the propositional statements that define the content. Responses were considered correct if both, the reason and the content choice of each item were correct. An item analysis was done considering the percentage of answers for each combination of content and reason level. The answers obtained for item 5 of the diagnostic test and its analysis are presented in Figure 3 and Table 3.

Procedure

Biological Sciences is a one year course with a six credit value (three per semester). Its design includes a human approach. The topic of mendelian genetics and meiosis is studied in the first part. The diagnostic instrument was administered by

TABLE 2

Especifications for the Diagnostic Test of Mendelian Genetics and Meiosis

Item	Propositions
1	M (2) (5)
2	M (1)
3	M (1)
4	M (1) (2) (5) (7)
5	M (1); G (4) (7) (9) (12)
6	M (1)(11)
7	M (11); G (7) (10) (11)
8	M (3) (4) (11) (12) (13)
9	M (11) (12)
10	G (4) (7) (8) (12) (13)
11	G (12) (13) (14)
12	G (12) (14)
13	G (3) (5) (6) (7) (9) (12)
14	G (2) (3) (8) (13) (14)
15	G (7) (8) (14)
16	G (12) (13) (14); T (4) (5)
17	G (11) (15); T (4) (5)
18	G (8); T (4) (5)
19	T (4) (5)
20	G (10) (11); T (2)
21	T (3); G (13) (14)

M = Meiosis

G = Mendelian Genetics

T = Typology of Problems

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the classroom teachers after the students completed the study of the topic under consideration, but before taking the achievement test prepared by the professors. One of the classes took the diagnostic test a second time, one week after the first administration. This was done as part of the process of validation to estimate the stability of the instrument by the test re-test.

RESULTS AND DISCUSSION

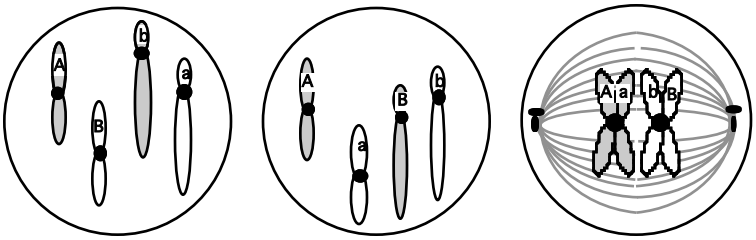
Table 4 presents a summary of psicometric characteristics of the Diagnostic Test of Mendelian Genetics and Meiosis. Students scores included values from 1 to 18 of apossible maximum of 21. The opportunity to write their justifications was used by 43

Figure 3. Item number 5

Of the following diagrams,

WHICH IS THE CORRECT REPRESENTATION OF ALLELES AND CHROMOSOMES IN A DIPLOID CELL?

a. b. c.



JUSTIFICATION FOR MY SELECTION:

1. Different alleles of a gene are located on identical copies of a chromosome.
2. Chromatids have identical alleles of a gene.
3. Homologous chromosomes have alleles of the same gene.
4. Alleles of the same locus are located in different positions of different chromosomes.
5. _____

TABLE 3

Percentage of students selecting the possible answers to item number 5.

	Justifications						
Content level	1	2	3	4	5	None	Total
a	2.0	.5	1.5	4.1	.5	-	8.6
b	14.7	4.6	10.2*	5.1	-	1.0	35.6
c	10.7	9.1	26.9	4.6	1.0	1.5	53.8

Note: 2% of students did not answer the question.
*Correct answer.
-No answer in this option.

students: five were correct answers and 38 revealed confusion (misunderstanding) or the affirmation that the items have more than one correct answer. Difficulty indexes range from 0.03 to 0.69, providing a wide range of difficulty. The discrimination range from .01 to .59 and the majority of items (19) surpassed 0.30, which is considered acceptable (Nunally, 1978). Although two of the items (5 and 7) shows a discrimination of less than 0.03 they were very effective in detecting misconceptions.

The reliability (internal consistency) of the instrument was calculated using Cronbach & coefficient and yielded a value of 0.61. The stability of the instrument (test - re-test) as revealed by Pearson r coefficient (0.70) at an alfa = .01, is considered acceptable.

TABLE 4

Characteristics of the Diagnostic Test of Mendelian Genetics and Meiosis

Content	: Meiosis (Item 1-9)		
	: Mendelian Genetics (Items 10-21)		
Number of items	: 21		
Item format	: Two-tier multiple choice		
Time to answer	: 45-60 minutes		
Average score	: 8.39		
Standard deviation	: 3.25		
Discrimination indices	: Mean	Range	Items
	0.39	<0.30	(2)
		.30-.39	(6)
		.40-.49	(9)
		.50-.59	(4)
Difficulty indices	: Mean	Range	Items
	0.39	.03-.19	(2)
		.20-.29	(2)
		.30-.39	(4)
		.40-.49	(7)
		.50-.59	(2)
		.60-.69	(3)
Reliability			
Internal consistency (Cronbach Alpha)	: .61		
Stability (Pearson r)	: .70		

The results of a confirmatory factor analysis revealed that all questions, except items 6 and 20 can be associated to one of five factors: F(1) the behavior of chromosomes during meiosis, F(2) the haploid and diploid condition, F(3) the principle of dominance and recessiveness, F(4) the relation between alleles and chromosomes and F(5) the heuristic or strategic knowledge of mendelian genetics. The criteria followed was a correlation r of 0.35 or more (Nachmias, 1987). Items 6 and 20, with correlations under 0.35, were associated to the factors they contributed more: four and five respectively. These questions were preassigned to these same factors.

The characteristics that described the participants of the study were submitted to correlation analysis with: the scores of the diagnostic test, achievement in mathematics

(defined as the score in the mathematic component of the College Admission Test), the scores associated to each factor of the confirmatory factor analysis, and the results of an achievement test offered by the classroom teachers. Table 5 and 6 show that the correlations with the scores of the achievement test and with achievement in mathematics, although low, are positive and significant ($\alpha = .01$). This may be due to the fact that the achievement and the diagnostic tests have content in common (related to factors 1, 2 and 4 but not 5). The correlation with mathematic achievement seems to indicate that mastering basic mathematics makes a positive difference when dealing with genetic related skills and concepts. The significant relation between factor five, the one including mendelian genetics strategic knowledge, and mathematic achievement adds strength to this indication.

TABLE 5

Relation Between the Variables that Describe the Population and the Scores in the Diagnostic Test of Mendelian Genetics and Meiosis

Variables	Correlation (r)	
High School Average	.0516	
College Average	-.0818	
Faculty	-.0408	
Gender	-.0255	
Achievement Test Score	.2113	**
Achievement in Mathematics (a)	.2496	
Years at the University	-.1156	

** Significant at an $\alpha = .01$

(a) Score in the College Admission Test

TABLE 6

Relation Between the Variables that Describe the Population and the Scores Associated to the Factors of the Confirmatory Factor Analysis

Variables	Correlation (r) Factors				
	F1	F2	F3	F4	F5
High School Average	.0718	.0881	.0388	.0445	.0141
College Average	.0047	.0151	.0276	-.0276	-.0404
Faculty	.1213	-.1457	-.0499	-.0157	-.0323
Gender	-.0686	-.0223	-.0743	.0087	.1167
Achievement Test Score	.2352**	.1836**	.1060	.1582*	.0064
Achievement in Mathematics (a)	.1873**	.1077	.0534	.2567**	.1936**
Years at the University	-.1739	-.0416	-.0449	.0387	-.1190

** Significant at an $\alpha = .01$
* Significant at an $\alpha = .05$
(a) Score in the College Admission Test

Table 7 list the misconceptions identified by the diagnostic test. The ones included were detected in 10% or more of the students following the recommendation of Haslam and Treagust (1987). The parenthesis includes references where the same conceptions were detected with a different methodology. It is appreciated that items vary in their capacity to detect misunderstandings.

Items 1 through 9, which are mostly related to meiosis, revealed that our students have conceptual difficulties similar to those of British, American, Australian and Israeli students when they: related the duplication of DNA to the meiotic phase of the cell cycle (item 1); revealed confusion with the concept chromosome and chromatid (item 4) and the location of alleles in the copies of the same chromosomes (item 3); defined haploid as cells containing pairs of chromosomes (item 6) or as cells entering the process of meiosis (item 8). The other misconceptions related to meiosis seems to be particular to this population. A considerable number of students (23.9%) defined a diploid nucleus as one containing chromosomes with two parts associated by the centromere (item 2). Others considered the diploid as the number of pair of chromosomes (27.4%) as revealed by item 4. For some students (27.9%) diploid cells combine during fertilization (item 8). For others (14.2%) the haploid number is an uneven number of chromosomes (item 6). Item 7 revealed difficulties related to the formation of tetrads and the movement of chromosomes during meiosis.

The most prevalent misconception is identified by item 7. Approximately one half of the students (51.3%) think that a cell AaBb after independent assortment (without crossover events) can lead to the formation of four types of gametes. They cannot distinguish between the types of gametes an AaBb individual can form and the ones that a cell can form. This is a misconception also prevalent among graduate students as revealed by our teaching experience and may be related to the use of diagrams. With impressive easiness students may think that all the cells presented in the diagrams of a process, including options, as is the case with independent assortment, are present at the completion of the process.

From question 10 to 21 the misconceptions detected reveal considerations of content and strategic knowledge of mendelian genetics, the social beliefs of students and maybe the confusion generated by inadequate management of technical concepts in textbooks. The principle of dominance and recessiveness is one hard to manage by our students. This implication derives from the answers to questions 10, 15 and 18 where, respectively, recessive alleles are considered rare and related to harmness, while the dominant conditions are the frequent or more abundant. From items 14 and 18 misconceptions were detected related to the so called "masculine dominance" of the Puerto Rican male, interfering with the learning of genetics. In this conceptions males are associated with a prototype of strongness, impulsiveness and rudity. If the male is also red-haired the connotation is exalted, because red-haired are considered hot-tempered and hyperactive. At the other extreme women are described as weak, and male dependent. For 27.4% of students dominant conditions are inherited from the male parent while for 14.2% the recessive conditions can be expressed by males or females. With these students the teaching effort was not successful overcoming the social vision of dominance that students bring with them to class versus the genetic concept which is part of the Biological Sciences course.

The conceptual understanding of the relation between genotype and phenotype generated misunderstandings among our students. Items 11, 12, 13 and 21 identified conceptualizations held by students in this case: the dominance or recessiveness of a genotype (item 13), the symbols (AA) and (aa) as representing heterozygoticy and the presumed equivalence between the number of phenotypes and the number of traits under study. Also that the dominant condition is the one that is expressed.

The Punnett square is presented in questions 16 and 20. From item 16 a common misconception is detected: to consider the divisions of the Punnett square as representing individuals. This seems to be related to a deterministic thinking in genetics, a science that requires probabilistic reasoning. It is possible that during the teaching-learning process the

square was used as an algorithmic solution without establishing the relation to the corresponding cellular processes. When students consider the divisions as representing individuals, they either fail to recognize the limitations of or use this tool in a mechanical way.

The analysis of genotypes in a Punnett square to determine the number of phenotypes (item 20) represents a difficulty if students do not understand the difference between a trait and the different forms or expressions of that trait (21.3%). Also the generation of gametes (procedural knowledge) from a genotypes homozygous for two traits revealed misunderstanding among 11.7% of the students when they indicated that one type of gamete was missing (the same as the one included in the square). Many texts books may be related to this aspect. They use to repeat the same type of gametes when illustrating crosses maybe for the sake of "appearance" of the Punnett square, reinforcing in students the mechanical use of this tool.

CONCLUSIONS

The analysis of the results of this study allows to state the following: the Diagnostic Test of Mendelian Genetics and Meiosis is effective in accomplishing the purpose for which it was designed, that is, the identification of specific misconceptions in mendelian genetics and meiosis. It also points out four areas of mendelian genetics and meiosis that generates major difficulties with conceptual understanding: the relation between meiosis and mendelian genetics, the relation between the genetic concepts; the meaning of the fundamental concepts; inherent aspects of probability and mathematics.

TABLE 7

Misconceptions Identified by the Diagnostic Test of Mendelian Genetics and Meiosis

Items	Misconceptions	Frequency (%)
1	The duplication of DNA is part of meiosis (Logden, 1982; Moll & Allen, 1986; Stewart, 1983)	13.2
2	A diploid nucleus contains chromosomes with two parts associated by the centromere	23.9
3	Homologous chromosomes are the ones inherited from the same parent	10.6
4	The terms chromosomes and chromatids are synonym (Pearson & Hughes, 1988a; 1988b; Smith, 1991)	17.5
	The diploid number is the number of pairs of chromosomes	27.4
5	Different alleles of a gene are located on identical copies of the same chromosome (Brown, 1990; Stewart, Hafner & Dale, 1990)	10.7
	Homologous chromosomes and chromatids are the same thing	26.9
6	An haploid number is an uneven number of chromosomes	14.2
	Haploid cells have chromosomes in pairs (Hackling & Treagust, 1984)	25.4
7	After independent assortment an AaBb cell can form 4 types of gametes (Kinnear, 1983; Stewart, Hafner & Dale, 1990)	51.3
	During meiosis tetrads move to opposite poles	11.2
8	Sexual reproduction of multicellular animals includes meiosis of haploid cells and fertilization of diploid cells (Tamir, 1990)	27.9
9	Diploid cells combines during fertilization	13.7
10	Recessive alleles are the least abundant in a population (Pearson & Hughes, 1988a; 1988b)	10.8
11	Homologous contrasting genotypes have the same phenotype	36.5
12	All individuals with dominant phenotype are of homozygous genotype	16.8
13	The genotype can be dominant or recessive (Hacking & Treagust, 1984; Simmons, 1987: Pearson & Hughes, 1988a; 1988b)	20.8
14	Dominant conditions are inherited from the father	27.4
15	Less frequent conditions are recessive	21.3
	Recessive alleles are responsible for harmful conditions (Pearson & Hughes, 1988a; 1988b)	16.8
16	The divisions of the Punnett square represent individuals (Simmons, 1987; Smith & Good, 1984)	26.4
	The symbols AA and aa represent heterozygous individuals (Simmons, 1987)	12.2
18	A condition is recessive if it is expressed by males and females	14.2
	The dominant conditions are the most frequent (Johnstone & Mahmoud, 1980; Simmons, 1987; Smith & Good, 1984)	11.1
19	The fraction 1/3 is equal to the proportion 3:1 (Smith, 1988)	20.8
21	Genetics traits and the associated alternate conditions are the same (Blosser, 1988; Pearson & Hughes, 1988a; 1988b)	21.3
	The phenotypes of the progeny of a cross are equivalent to the number of traits under study	21.3
	Individuals homozygous for two traits produce two types of gametes	10.7

Taking into consideration the teaching of mendelian genetics and meiosis at college level this study states that conceptual understanding can be promoted with the following recommendations. The events of the DNA duplication and meiosis should be emphasized as part of the cell cycle. This will result in a more clear understanding of why the chromosomes appear as double structures at the beginning of meiosis. The management of genetics and meiosis should be an integrated one and the instruction of meiosis needs to emphasize the location of alleles in the chomosomes. There is evidence that if this is done the effectiveness of teaching rises (Blosses, 1988; Johnstone & Mahmoud, 1980; Smith, 1991). When using diagrams of the process, the chromosomal events should be the considered in a secuence leading to haploid products. The students must understand that the cells diagramed lead to these products and are not there when the process is completed. Text book writers and editors must be aware of the diverse effects of diagrams which are not always the ones expected.

The inter-relation of concepts need to be stressed by using diagrams and models prepared by the students. Our experience have shown that to follow a diagram or model is less effective for conceptual understanding than preparing the diagram or model. Also the use of analogies will help to established relations and contribute to the relevance of the new knowledge. When the importance of knowing what a concept is and what it is not is stressed we are promoting the establishment of meaningful relations.

The lack of precision in the use of genetic terms generates confusion and may contribute in a subtle way to misunderstandings. Terms like gene, allele, haploid, diploid should be described in the clearest way considering its correct and incorrect use. We need the participation of experts in the process, evaluating, pointing out errors, writing and editing books and other reference materials surpassing what appears to be a common and erroneous point of view in our country: to consider research in science education as less important than research in science.

In the case of mathematics and probability in genetics, with the positive correlation established in this study between execution in the diagnostic test and mathematic achievement and also the studies of Smith (1988), Longden (1982) and Walter, Mertens and Hendrix (1979) and others, there are indicators that these topics should be included as part of the content and skills of mendelian genetics. Omitting it, as is the general practice in the Biological Sciences course, can generate great confusion in relation to, among other things, the Punnett square, proportions in the progeny, the formulation of hypothesis and the interpretation of facts. This was appreciated from the analysis of various items of the diagnostic test. Also an

understanding of probability is part of the general education we need to deal day by day in our lives.

For the management of misconceptions in mendelian genetics and meiosis this study recommends a direct and specific treatment. The duty of the teacher is the design of the diagnosis. The responsibility of the student is being alert to their conceptions and comparing them to the scientifically established. Another consideration which is basic and related to the design of the diagnostic test is to request during the student learning activities levels of knowledge that surpass recall. This opportunity is offered in genetics teaching specially in the problem solving process. This should not be misused, given primacy to the solution process and not to the mere solution or product.

One of the most complete philosophers of our times, Paulo Freire stated "Nadie educa a nadie, pero nadie se educa solo" (1978). This is an affirmation of the value of the teacher and the companion of study as facilitators of the learning process. For Freire as for the constructivist (Ausubel, 1968), the control and the responsibility of learning resides in the learner as an active participants of what he names as a "educación problematizadora".

The Diagnostic Test of Mendelian Genetics and Meiosis by its design and construction is relevant and places the locus of learning on the student. It presupposes the opportunity for a learning experience ("Learning while testing"). It was designed for students of an introductory biology course among whom a transformation in their way of thinking is urgent. The teaching process must propiciate the movement from a level of knowledge dependent on recall to higher levels. The fact that the diagnostic test requires justifications for the answers promotes the development of the skills of comprehension, analysis, evaluation and problem solving, among others. The nature of the test gives space for adjustments considering the needs of the student population at a particular time.

The instrument design facilitates the work of the teacher. The open part of the test, where the student writes other reasons not included in the items, allows the teachers a more precise diagnosis of the conceptual understanding of their students. This promotes their role as facilitators of learning. An effective teaching learning process must explore and diagnose. One cannot talk about change, conceptual change, if the state of knowledge is not established. To help in this task, when mendelian genetics and meiosis are considered, have been the purpose of the Diagnostic Test of Mendelian Genetics and Meiosis.

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Copies of Tables

TABLE 1

Propositions of Mendelian Genetics and Meiosis

Meiosis

1. Diploid organisms have pairs of homologous chromosomes.
2. Cellular and sexual reproduction require the duplication of DNA.
3. The sexual reproduction of diploid multicellular animals have gametogenesis as a requisite.
4. Gametogenesis includes cellular diferentiation and m,eiosis.
5. The duplication of DNA is a pre-requisite of meiosis.
6. The process of meiosis includes two nuclear divisions, such that the first is a prerequisite of the second.
7. The pairing of homologous chromosomes, synapsis, and the formation of tetrads are events that occur during the first meiotic division.
8. The formation of tetrads allows for recombination.
9. Independent assortment of chromosomes and segregation are events of the first meiotic division that follow the formation of tetrads.
10. The separation of sister chromatids and the formation of haploid nuclei occur during the second meiotic division.
11. As a result of meiosis the chromosome number of the gametes is haploid.
12. Gametes combines at random during fertilization to form zygotes.
13. With the formation of the zygote the diploid number of the species is restored.
14. Growth is the result of the cellular reproduction of the zygote.
15. Cellular reproduction includes mitosis and citocinesis.
16. Growth of the zygotes results in diploid multicellular animals

Mendelian Genetics

1. Mendelian genetics deals with diploid organisms that have a genotype and a phenotype.
2. The phenotypes are constituted by the traits of the members of the species.
3. The genotype is constituted by the pair of genes present in the individuals.
4. Alleles are the alternative forms or variants of a gene.
5. Each trait exhibited two variant: one dominant and one recessive.
6. Genes are related to alleles as traits are related to their variants or forms.

7. Alleles can be of two types: dominant or recessive. They are represented by big or small letters respectively.
8. The presence of the dominant allele mask the expresion of the recessive.
9. Alleles are present in pairs.
10. The pairs of alleles undergoes segregation and independent assortment during meiosis.
11. As a result of segregation and independent assortment gametes would have an allele of each pair in all possible combinations provided by the genotype.
12. For each trait there are three possible allelic combinations for the genotype: homozygous dominant, heterozygous and homozygous recessive.
13. The expression of the homozygous recessive genotype is recessive.
14. The genotypes homozygous dominant and heterozygous have a dominant expression.
15. If an individual of dominant phenotype is test cross, its genotype can be inferred.

Typology of problems

1. Problems in mendelian genetics can be classified in two types: Those that go from the causes (genotype of the parents is known) to the effects and those that go from the effects (phenotype and/or genotype of the progeny is known) to the causes.
2. If the genotypes of the parents are known the type of gametes and the proportions in which they should be form can be predicted considering segregation and independent assortment.
3. The Punnett square can be used to predict the variants and the phenotypic and genotypic proportions of the progeny. It is presumed that the union of gametes occurs at random.
4. If the phenotypes of the parents and the progeny of a cross are known the genotypes associated to each one of the traits can be determine.
5. To determine the genotypes, pair the phenotypes of the parents and the progeny with the six possible crosses for each one of traits.

TABLE 2

Especifications for the Diagnostic Test of Mendelian Genetics and Meiosis

Item	Propositions
1	M (2) (5)
2	M (1)
3	M (1)
4	M (1) (2) (5) (7)
5	M (1); G (4) (7) (9) (12)
6	M (1)(11)
7	M (11); G (7) (10) (11)
8	M (3) (4) (11) (12) (13)
9	M (11) (12)
10	G (4) (7) (8) (12) (13)
11	G (12) (13) (14)
12	G (12) (14)
13	G (3) (5) (6) (7) (9) (12)
14	G (2) (3) (8) (13) (14)
15	G (7) (8) (14)
16	G (12) (13) (14); T (4) (5)
17	G (11) (15); T (4) (5)
18	G (8); T (4) (5)
19	T (4) (5)
20	G (10) (11); T (2)
21	T (3); G (13) (14)

M = Meiosis

G = Mendelian Genetics

T = Typology of Problems

TABLE 3

Percentage of students selecting the possible answers to item number 5.

	Justifications						
Content level	1	2	3	4	5	None	Total
a	2.0	.5	1.5	4.1	.5	-	8.6
b	14.7	4.6	10.2*	5.1	-	1.0	35.6
c	10.7	9.1	26.9	4.6	1.0	1.5	53.8

Note: 2% of students did not answer the question.
*Correct answer.
-No answer in this option.

TABLE 4

Characteristics of the Diagnostic Test of Mendelian Genetics and Meiosis

Content	:	Meiosis (Item 1-9)		
	:	Mendelian Genetics (Items 10-21)		
Number of items	:	21		
Item format	:	Two-tier multiple choice		
Time to answer	:	45-60 minutes		
Average score	:	8.39		
Standard deviation	:	3.25		
Discrimination indices	:	Mean	Range	Items
		0.39	<0.30	(2)
			.30-.39	(6)
			.40-.49	(9)
			.50-.59	(4)
Difficulty indices	:	Mean	Range	Items
		0.39	.03-.19	(2)
			.20-.29	(2)
			.30-.39	(4)
			.40-.49	(7)
			.50-.59	(2)
			.60-.69	(3)
Reliability				
Internal consistency (Cronbach Alpha)	:	.61		
Stability (Pearson r)	:	.70		

TABLE 5

Relation Between the Variables that Describe the Population and the Scores in the Diagnostic Test of Mendelian Genetics and Meiosis

Variables	Correlation (r)
High School Average	.0516
College Average	-.0818
Faculty	-.0408
Gender	-.0255
Achievement Test Score	.2113 **
Achievement in Mathematics (a)	.2496
Years at the University	-.1156

** Significant at an $\alpha = .01$

(a) Score in the College Admission Test

TABLE 6

Relation Between the Variables that Describe the Population and the Scores Associated to the Factors of the Confirmatory Factor Analysis

Variables	Correlation (r) Factors				
	F1	F2	F3	F4	F5
High School Average	.0718	.0881	.0388	.0445	.0141
College Average	.0047	.0151	.0276	-.0276	-.0404
Faculty	.1213	-.1457	-.0499	-.0157	-.0323
Gender	-.0686	-.0223	-.0743	.0087	.1167
Achievement Test Score	.2352**	.1836**	.1060	.1582*	.0064
Achievement in Mathematics (a)	.1873**	.1077	.0534	.2567**	.1936**
Years at the University	-.1739	-.0416	-.0449	.0387	-.1190

** Significant at an $\alpha = .01$

* Significant at an $\alpha = .05$

(a) Score in the College Admission Test

TABLE 7

Misconceptions Identified by the Diagnostic Test of Mendelian Genetics and Meiosis

Items	Misconceptions	Frequency (%)
1	The duplication of DNA is part of meiosis (Logden, 1982; Moll & Allen, 1986; Stewart, 1983)	13.2
2	A diploid nucleus contains chromosomes with two parts associated by the centromere	23.9
3	Homologous chromosomes are the ones inherited from the same parent	10.6
4	The terms chromosomes and chromatids are synonym (Pearson & Hughes, 1988a; 1988b; Smith, 1991)	17.5
	The diploid number is the number of pairs of chromosomes	27.4
5	Different alleles of a gene are located on identical copies of the same chromosome (Brown, 1990; Stewart, Hafner & Dale, 1990)	10.7
	Homologous chromosomes and chromatids are the same thing	26.9
6	An haploid number is an uneven number of chromosomes	14.2
	Haploid cells have chromosomes in pairs (Hackling & Treagust, 1984)	25.4
7	After independent assortment an AaBb cell can form 4 types of gametes (Kinnear, 1983; Stewart, Hafner & Dale, 1990)	51.3
	During meiosis tetrads move to opposite poles	11.2
8	Sexual reproduction of multicellular animals includes meiosis of haploid cells and fertilization of diploid cells (Tamir, 1990)	27.9
9	Diploid cells combines during fertilization	13.7

10	Recessive alleles are the least abundant in a population (Pearson & Hughes, 1988a; 1988b)	10.8
11	Homologous contrasting genotypes have the same phenotype	36.5
12	All individuals with dominant phenotype are of homozygous genotype	16.8
13	The genotype can be dominant or recessive (Hacking & Treagust, 1984; Simmons, 1987: Pearson & Hughes, 1988a; 1988b)	20.8
14	Dominant conditions are inherited from the father	27.4
15	Less frequent conditions are recessive	21.3
	Recessive alleles are responsible for harmful conditions (Pearson & Hughes, 1988a; 1988b)	16.8
16	The divisions of the Punnett square represent individuals (Simmons, 1987; Smith & Good, 1984)	26.4
	The symbols AA and aa represent heterozygous individuals (Simmons, 1987)	12.2
18	A condition is recessive if it is expressed by males and females	14.2
	The dominant conditions are the most frequent (Johnstone & Mahmoud, 1980; Simmons, 1987; Smith & Good, 1984)	11.1
19	The fraction 1/3 is equal to the proportion 3:1 (Smith, 1988)	20.8
21	Genetics traits and the associated alternate conditions are the same (Blosser, 1988; Pearson & Hughes, 1988a; 1988b)	21.3
	The phenotypes of the progeny of a cross are equivalent to the number of traits under study	21.3
	Individuals homozygous for two traits produce two types of gametes	10.7