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Article

Understanding of Genetic Information in Higher Secondary Students in Northeast India and the Implications for Genetics Education

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Since the work of Watson and Crick in the mid-1950s, the science of genetics has become increasingly molecular. The development of recombinant DNA technologies by the agricultural and pharmaceutical industries led to the introduction of genetically modified organisms (GMOs). By the end of the twentieth century, reports of animal cloning and recent completion of the Human Genome Project (HGP), as well techniques developed for DNA fingerprinting, gene therapy and others, raised important ethical and social issues about the applications of such technologies. For citizens to understand these issues, appropriate genetics education is needed in schools. A good foundation in genetics also requires knowledge and understanding of topics such as structure and function of cells, cell division, and reproduction. Studies at the international level report poor understanding by students of genetics and genetic technologies, with widespread misconceptions at various levels. Similar studies were nearly absent in India. In this study, I examine Indian higher secondary students' understanding of genetic information related to cells and transmission of genetic information during reproduction. Although preliminary in nature, the results provide cause for concern over the status of genetics education in India. The nature of students' conceptual understandings and possible reasons for the observed lack of understanding are discussed.

Keywords: genetic information, cells, reproduction, higher secondary students, northeast India

INTRODUCTION

Almost 100 yr after coining of the terms "genetics" (William Bateson in 1906) and "gene" (Wilhelm Johansen in 1909), the field of genetics has expanded to cover many areas beyond merely the study of inheritance. A good understanding of genetics now requires knowledge about structure and function of the cell and its organelles and of cell division and reproduction.

Genetics is one of the most difficult subjects in the biology curricula at the primary and secondary school (Hallden, 1988; Kelly and Monger, 1974; Longden, 1982) and college and university levels (Brumby, 1979, 1984; Johnstone and Mahmoud, 1980; Kindfield, 1994a, b). Studies in other countries have shown that understanding of genetics and its various aspects is poor among students of various levels and among the population in general (Lewis and Wood-Robinson, 2000; Lewis *et al.*, 2000a, b, c; Lock and Miles, 1993; Lock *et al.*, 1995; Marbach-Ad, 2001; Marbach-Ad and Stavy, 2000; Michie *et al.*, 1995; Ponder *et al.*, 1996; Scriver, 1993; Wood-Robinson, 1994, 1995; Wood-Robinson *et al.*, 2000). Genetics education has become increasingly important with the advent of recombinant DNA technologies and the subsequent emergence and availability of genetically modified food and organisms (GMOs). Issues such as DNA screening, cloning, and GMOs are hotly debated in various countries, including India, where a high level of scientific literacy is needed among the general public to address such issues and give informed consent about uses of the new technologies (Dawson and Schibeci, 2003). To the best of my knowledge, almost no reports in India have examined students' knowledge and understanding of biology topics related to genetics. In this study, although preliminary in nature, I begin to address this area of science education

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research, which has relevance for curriculum developers, textbook writers, and teachers.

Indian Educational System

The present educational system in India includes school, college, and university levels. The school system extends from kindergarten to class XII, which has four categories: primary (I–V), middle (VI–VIII), secondary (IX–X), and junior college or higher secondary (XI–XII) levels (Mahajan and Chunawala, 1999). Although the higher secondary level (XI and XII) is considered part of school education, it is taught mostly in undergraduate colleges. Efforts are ongoing to open these classes in schools by upgrading them from secondary to higher secondary standards and providing necessary manpower and infrastructure.

The National Council for Educational Research and Training (NCERT), an autonomous Central Government organization, prepares the broad guidelines of the school syllabus up to the higher secondary level. It also publishes textbooks, which are followed by Central Schools and funded by the Central Government, particularly for the children of Central Government employees with transferable jobs located in different parts of the country. State governments have their own State Education Departments with government-aided schools, which follow the broad pattern of the syllabus laid down by NCERT. Government-affiliated private schools, which follow either the syllabus of NCERT or the State Educational Boards, also operate in many states. Portions of the cell biology and genetics syllabus taught at the higher secondary level in the Meghalaya Board of School Education, Meghalaya, India, where this study was conducted are given in Table 1.

In India, the topic of genetics is introduced either at the secondary level (classes IX–X) or at the higher secondary level (classes XI–XII). In this study, the sample of students studied genetics from class XI only.

METHODOLOGY

I examined knowledge and understanding of concepts related to cell biology and reproduction among class XII students. Both of these topics were judged to be extremely important for good conceptual understanding of genetics.

Questionnaire Used

A written questionnaire, developed by Lewis *et al.* (2000a, c) as part of the "Learning in Science Research Group," Leeds University (United Kingdom), was used with permission. The questionnaire has two parts: the "Cells" section and the "Reproduction" section. It combines both fixed- and free answer–type questions. Even though the questionnaire was used in the United Kingdom for middle school children, the same questionnaire was used in this study for higher secondary students. Use of the questionnaire in this study

Table 1. Portions of cell biology and genetics syllabus taught at the higher secondary level in Meghalaya Board of School Education, Meghalaya, India

Subject	Topic	Item
Genetics (classical)	Continuity of life	Heredity, variation
	Mendel's laws of inheritance	Incomplete dominance, multiple allelism, quantitative inheritance
	Chromosomes	Bacterial and eukaryotic cells; parallelism between genes and chromosomes, genome; linkage and crossing over; gene mapping; recombination; sex chromosomes, sex determination, sex-linked inheritance; mutational and chromosomal aberrations; human genetics—methods of study, genetic disorders
Genetics (molecular)	DNA as genetic material	DNA structure and its replication; structure of RNA and its role in protein synthesis; gene expression, transcription, and translation in prokaryotes and eukaryotes (regulation of gene expression, induction and repression, housekeeping genes, nuclear basis of differentiation, and development); oncogenes
	Basics of recombinant DNA technology	Cloning; gene banks; DNA fingerprinting; genomics principles and applications; transgenic plants, animals, and microbes
Cell biology	Cell as basic unit of life	Discovery of cell, cell theory, cell as a self-contained unit; prokaryotic and eukaryotic cells; unicellular and multicellular organisms; ultrastructure of the prokaryotic and eukaryotic cell–cell wall, cell membrane, unit membrane concept (fluid mosaic model); membrane transport; cell organelles and their functions—DNA and RNA, nucleus, mitochondria, plastids, endoplasmic reticulum, Golgi complex, lysosomes, microtubules, centriole, vacuole, cytoskeleton, cilia and flagella, ribosomes
	Cell cycle and cell division	Cell cycle—significance of cell division, amitosis, mitosis and meiosis; karyotype analysis

was justified because it had been prepared by an experienced research group working in genetics education and already had been tested among students (Lewis and Wood-Robinson, 2000; Lewis *et al.*, 2000a, b, c). In addition, the questionnaire was designed to assess conceptual understanding of topics also included in Indian curriculum. The same responses considered as correct in the previous study (Lewis *et al.*, 2000a, c), were taken as correct responses to the multiple choice questions in this study.

Sample of Students

The study was conducted with a sample of 289 students (158 boys and 131 girls) of class XII (16–18 years old) from three different undergraduate colleges in Shillong, Meghalaya, a state in northeast India. Among these colleges, one was for boys only, one was for girls only, and the third was coeducational. The same syllabus, laid down by the State Educational Board was followed in all three colleges. The students had the same science backgrounds and appeared in the selection examination (an examination conducted by individual colleges for their own student) after completing their 2-yr higher secondary courses to qualify for the final examination conducted by the Board. They would have been expected to know the answers to the questions asked in the study questionnaire.

Administration of Questionnaire to the Students

The questionnaires were administered at each of the respective colleges within the class periods of 45 min with the help of the class teachers. Questionnaires were distributed to all students present in the class. Care was taken to avoid any exchange of information or ideas among students.

RESULTS

Cells Section

A detailed description of the Cells section of the questionnaire is available in Lewis *et al.*, (2000c). In short, the questions examined knowledge and understanding of the genetic relationship between cells of the same individual, as well as between cells of different individuals. Emphasis was given to estimating students' awareness of the concept that "all somatic cells contain the same genetic information and that each sperm contains a unique combination of genetic information" (Lewis *et al.*, 2000c). Diagrams of cheek, nerve, and sperm cells appeared at the beginning of the questionnaire.

For the first four questions of the study reported here, students were asked to compare four pairs of cells from the same individual (Robert, a male; see Lewis *et al.*, 2000c), as given below.

a. Two somatic cells of the same type (cheek cell).
b. Two somatic cells of different types (a cheek cell and a nerve cell).
c. One somatic cell and one germ cell (a cheek cell and a sperm cell).
d. Two germ cells (sperm cells).

Question e asked for a comparison of the genetic information of two somatic cells (cheek cells) of two different persons (Robert and John). Student responses to these five questions are summarized in Table 2.

Responses to each of the five questions were coded, and the frequency of different responses was noted. It was found that only 132 students (46% of the total number of students) gave reasons for their responses to all of the questions; they responded explicitly but not always correctly.

Because examining student understanding was an important objective of the study, a second analysis was conducted on the 132 questionnaires in which students gave explicit views (correct or incorrect) with reasoning to all the questions asked.

In an earlier study of secondary school children (Lewis *et al.*, 2000c), student responses to questions in this section pointed toward two problematic concepts—all cells within an individual carry the same information (relates to an understanding of mitosis), and sex cells are an exception to this rule (relates to an understanding of meiosis). Using these

Table 2. Student responses in the Cells section

Question [science concept]	Possible responses	Percentage of students giving response (N = 289)
a. *If you could take two of Robert's cheek cells, would the genetic information*	Same	77
in them be: the same/different/don't know.	Different	15.5
Please give reasons for your answers. [Cells of same tissue of same person]	Don't know	7.5
b. *If you could take one of Robert's cheek cells and one of Robert's nerve cells,*	Same	37
would the genetic information in them be: the same/different/don't know.	Different	63
Please give reasons for your answers. [Cells of different tissues from same person]	Don't know	
c. *If you could take one of Robert's cheek cells and one of Robert's sperm cells,*	Same	57.5
would the genetic information in them be: the same/different/don't know.	Different	42.5
Please give reasons for your answer. [Cells of reproductive tissue of same person]	Don't know	
d. *If you could take two of Robert's sperm cells, would the genetic information*	Same	80.5
in them be: the same/different/don't know.	Different	16
Please give reasons for your answer. [Cells of reproductive tissue of same person]	Don't know	3.5
e. *If you take Robert's cheek cell and John's cheek cell would the genetic information*	Same	16
in them be: the same/different/don't know.	Different	82
Please give reasons for your answer. [Cells of same tissue of different person]	Don't know	2

two concepts, students' "understanding" can be described as falling within one of the following categories:

- understands the basic idea and makes a distinction between somatic and sex cells;
- understands the basic idea, but does not distinguish between somatic and sex cells;
- has a basic belief that genetic information within a cell relates to cell function but recognizes that there is a difference between somatic and sex cells;
- has a basic belief that genetic information within a cell relates to cell function and does not distinguish between somatic and sex cells;
- gives confused or incorrect responses.

When the 132 questionnaires of students who gave reasons for their answers were examined, several different student "understandings" or views were evident. To avoid repetition, these views are described by category below, with mention of the different questions that elicited each particular explanation from students.

1. *Cells of the same individual contain the same genetic information (without distinguishing the somatic and germ cells).* Eighty-nine percent of students (117 of 132) used this rationale for an answer. For example, question a (cheek:-cheek) received explanations such as: "Cells of the same person should always carry the same genetic information" (response: Same, student 53); "The cells are from the same person" (response: Same, student 76); or "Because it is from the same individual" (response: Same, student 201). This explanation also was applied to questions b (cheek:-nerve) and c (cheek:sperm): "The cells are from the same person" (response: Same, students 53, 76). The same reason was applied even in comparing the sex cells of the same individual, as noted in question d (sperm:sperm).
2. *Only cells of same type/same part of the body contain the same genetic information (without distinguishing the somatic and germ cells).* This reason was given by 30% of students, mostly to questions b and c, and also for question a. Examples include responses to question a (cheek:cheek): "Since they belong to the same type" (response: Same, student 49); or "Because they are from the same part of the body" (response: Same, student 8). Students also applied this explanation to questions b (cheek:nerve) and c (cheek:sperm): "Because they are from different parts of body" (response: Different, students 8 and 222).
3. *Only cells of same shape/structure contain the same genetic information (without distinguishing the somatic and germ cells).* Twenty percent of the students cited this reason, particularly for questions b and c. Some students included the functional aspect with shape, for example, question b (cheek:nerve): "They have different shape and function" (response: Different, student 46); or "Because of the different structure of the cells" (response: Different, student 201). Similar explanations were given for question c (cheek:sperm): "They have different shape and function" (response: Different, student 46).
4. *Only cells of same function contain the same genetic information (without distinguishing the somatic and germ cells).* Approximately 50% of the students used this reason for questions b, c, and d, and 5% applied it to question a. Typical explanations for question a (cheek:cheek) were: "They are from the same person having the same function" (response: Same, student 48) or "If we take part of Robert's two cheeks they won't be different because both his cheeks perform the same function hence genetic information will be the same" (response: Same, student 222). Rationale for answers to question b (cheek:nerve) also applied this concept: "They are for different function" (response: Different, student 48). Similarly, this argument was used for question c (cheek:sperm): "They are for different function" (response: Different, student 48) or "Because they are from different parts of the body having different functions" (response: Different, student 8), as well as to question d (sperm:sperm): "Because they perform the same function" (response: Same, student 8).
5. *Cells of different individuals contain different genetic information.* This reason was given by most of the students to answer question e (cheek:cheek, from different people): "Because every person has got different genetic information" (response: Different, student 48); "Because the cells are from two different persons" (response: Different, student 76); or "Because the two belong to different person" (response: Different, student 201).
6. *Genetic information is related to the DNA present in cell(s)/individual(s).* Only three students tried to link genetic information with DNA content of cells or individuals. This was observed in explanations for questions a (cheek:cheek): "Because it contains the same DNA as in other cheek cells" (response: Same, student 119) and e (cheek:cheek, from different people): "Because they possess different DNA" (response: Different, student 8) or "Because genetic information in different DNA will be different in them" (response: Different, student 19).
7. *Genetic information is related to X and Y chromosomes of sperm.* Many students (29% of 132) who thought that the genetic information of two sperm cells would be different reasoned that the genetic information in sperm is related to the X or Y chromosome it contains. For example, this reasoning was given for question d (sperm:sperm): "Because some sperms have X chromosomes, some have Y chromosomes" (response: Different, student 69) or "Genetic information in X chromosome is different from Y chromosome" (response: Different, student 184).
8. *Reasons related to other responses*. Widespread confusion was observed among the incorrect responses of students for question a (23% of the total sample) and with the correct answers to question d (18.5% of the total sample). For example, some responses to question a (cheek:cheek) were: "Because the cheek cell will be increased by double the original number" (response: Different, student 236; confusion about whether the genetic information is doubled after division) or "Because the composition of the cells in the cheeks will be different. Chromosomes gives us genetic information about the person. The chromosomes are only found in sex cells" (response: Different, student 131; confusion that chromosomes are present only in sex cells), whereas responses to question d (sperm:sperm) included: "Because one gene may be recessive and the other may be dominant" (response: Different, student 135; confusion about genes and genetic information); "Because they do not have the same structural and functional units" (response: Different, student 61; confusion regarding the structure, function, and genetic information of cells); and "Since no two cells are alike in their structure and sometimes function"

(response: Different, student 74; confusion that each cell has separate genetic information for its structure and function).

In addition, other important observations can be made about student responses in the Cells section of the questionnaire.

- None of the students gave correct answers to all five questions.
- Some of the students, when responding to questions a through c, which asked about genetic information within the same individual, gave views falling in more than one category. For example, in the case of student 201, the reason for her response to question a falls in the first category, but her reasons for questions b and c fall in the third category. Similar cases are found in the responses of students 8 and 222 (categories 2 and 4), and 76 (categories 1, 3, and 4).
- It also is important to note that none of the students mentioned that sex/germ cells differ in their genetic makeup in the same individual because of random combinations of homologous chromosomes during meiosis and crossing over during cell division.

Overall, students could not distinguish between somatic and sex cells. The inability to understand the genetic difference between sperm cells was perhaps a misunderstanding of the two types of cell division (mitosis and meiosis). This possibility was further supported when the same students responded to another section, "Cell Division" with questions about mitosis and meiosis (unpublished data). The students presented inconsistent views, particularly about the genetic information within the same individual.

Reproduction Section

As mentioned in Lewis *et al.* (2000a), in this section, students were asked to "compare chromosome number in the egg and sperm; indicate the number of chromosomes in the fertilized egg; explain the purpose of sexual reproduction; indicate the type(s) of reproduction that takes place in plants." This section had three parts. The same choices for correct responses used by Lewis *et al.* (2000a) are used in this study.

Part 1 consisted of questions 1 and 2 of the Reproduction section and examined student knowledge of the following concept: *In animals, when a sperm cell fertilizes an egg cell, a new cell is formed. This is the process of sexual reproduction. This new cell develops into a new animal.* A diagram was given showing a sperm fertilizing an egg containing three chromosomes leading to the formation of a zygote.

Student responses to each question are given in Table 3. Because student explanations cannot be aggregated for the entire section, explanations of responses to each question are reported below.

Question 1. *If an egg cell contained the chromosomes shown in the diagram above, what chromosomes do you think the sperm cell would contain? Please give reasons for your answer. (The choices were 6, 5, 3, or 2 chromosomes or "Don't know").* The correct answer to this question was expected to be 3 (with the understanding that both germ cells contain the same [n] number of chromosomes), even though in some animals in which sex determination is based on the XX/XO system, sperm contain one chromosome fewer than eggs. Because this information is not taught at the school level, students were not expected to know this exception.

As noted in Table 3, 65% of the students correctly identified that the chromosome number in sperm will also be the same (n = 3). Of these, 39% gave valid explanations for their responses, such as: "Same number of chromosome of an egg cell and sperm cell form a zygote" (student 48) or "Since egg has 3 chromosomes, sperm will also have 3 chromosomes" (student 30). Among the other responses, 12.5% of students thought that the sperm would contain only two chromosomes.

Table 3. Student responses in the Reproduction section

Question [science concept]	Possible responses	Percentage of students giving response (*N* = 289)
1. *If an egg cell contained the chromosomes shown in the diagram above, what chromosomes do you think the sperm cell would contain? Please give reasons for your answer.* [Number of chromosomes in sperm, if egg contains 3 chromosomes]	6	7.5
	5	1.0
	3	65.0
	2	12.5
	Don't know	14
2. *Which chromosomes do you think would be in the new fertilized cell? Please give reasons for your answer.* [Number of chromosomes in fertilized egg]	6	42.5
	5	2.0
	3	29
	2	9.5
	Don't know	17
3. *Why animals that can reproduce asexually still need to reproduce sexually? I have no idea/I have some idea (I think that . . .).* [Advantage of sexual reproduction over asexual reproduction]	Some idea/ plausible explanation	43.5
	No idea/don't know	56.5
4. *Tick the box against the choice (sexual/asexual/both sexual and asexual/don't know), you think, plants reproduce and give your reason.* [Mode of reproduction in plants]	Sexual	6
	Asexual	15
	Both	76
	Don't know	3

Incorrect explanations were related mainly to the following misconceptions: confusion regarding the term haploid/diploid, "Because it is diploid (2n) chromosomes" (student 61); and confusion that the reproductive cells contain only X and Y chromosomes: "Because a sperm cell contains an X and Y chromosomes" (student 90) or "Because a sperm cell can not have more than 2 chromosomes" (student 3).

Some students (7.5%) thought that the sperm cell would have six chromosomes. These explanations were difficult to categorize. The students had widespread misconceptions, such as: "Because the sperm unite 3 chromosomes of egg cell" (student 76); "The sperm will contain double the number of chromosomes" (student 1); or "Twice, since it undergoes meiosis" (student 201).

One percent of students opted for five chromosomes, giving as a rationale that sperm have more chromosomes: "Because sperms have more chromosomes than egg" (student 11). Fourteen percent of students did not know the answer. One student argued, "Because we can not predict the chromosomes in the sperm cell just by observing the chromosomes in the egg cell" (student 63).

Question 2. *Which chromosomes you think would be in the new fertilized cell? Please give reasons for your answer.* Of the students who gave the correct response (42.5%) to this question (there should be six chromosomes in the fertilized egg), only 40% gave a valid reason for their response, such as: "3 chromosomes of sperm and 3 chromosomes of the egg will be present in the fertilized cell" (student 3). The rest of the students provided invalid reasons and had large-scale confusion about the entire process. Examples include: "The process involved is mitosis" (student 76) or "Because in the egg cell there is already 3 chromosomes in it, so it will reproduce 2 more egg cell to form a new fertilized cell" (student 23). Twenty-nine percent of the students thought that there should be three chromosomes in the fertilized egg: "These chromosomes (of sperm and egg) unite with each other to form a zygote" (student 48; confusion between chromosome and cell) and "Number of chromosomes is half of its parent" (student 21; confusion that the number of chromosomes reduces after each generation). Among other responses, 9.5% of students thought that there should be only two chromosomes: "'n' chromosome of sperm and 'n' chromosome of ovum will make it '2n'" (student 14; confusion that the 'n' number of chromosomes in sperm and egg is only one) or "X chromosome and Y chromosome will join together" (student 9; confusion that the sperm and egg cell carry only sex chromosomes X or Y). Two percent of the students thought that there would be five chromosomes. Their reasoning was based mainly on the understanding that the two chromosomes of the sperm (mistakenly predicted in the earlier question) would join with the three chromosomes of the egg (e.g., "… since 2 chromosomes and 3 chromosomes fuse together"). Seventeen percent of the students had no idea how to answer this question: "Similarly, as we cannot predict the chromosome in the sperm cell, we can not predict anything about the chromosome of the new fertilized cell" (student 63).

Part 2 of the Reproduction section consisted of one question, given below with student responses and explanations.

Question 3. *Why (do) animals that can reproduce asexually still need to reproduce sexually? I have no idea/I have some idea (I think that …).* For this question, 56.5% had no idea. The rest (43.5%) had some idea, although when they were asked to elaborate, only 15% of them could give a scientific explanation indicating that sexual reproduction helps in the evolutionary process: "So that the new animal produced after sexual reproduction can have mixed characters of both the parents" (student 209). The majority of students gave an inappropriate reason, such as, "… simple animal would reproduce sexually during favorable condition and asexually during unfavorable condition (food, temperature etc.)" (student 48).

Part 3 was made up of the following single question.

Question 4. *Tick the box against the choice (sexual/asexual/both sexual and asexual/don't know), you think, plants reproduce and give reason.* For this question, 76% ticked that plants reproduce both by sexual and asexual methods. In their reasoning, only 39% of students gave a valid response: "By asexual reproduction there is only increase in number, sexual reproduction helps in mixing of characters" (student 37) or "Plants reproduce asexually to multiply only, they undergo sexual reproduction to have better variety" (student 209). A majority of the students expressed an idea similar to the thinking that "plants reproduce asexually in unfavorable condition and sexually in favorable condition" (student 48). A good number of students also thought that lower plants (e.g., algae) undergo asexual reproduction, and only the higher plants reproduce sexually. No student mentioned pollination, self fertilization, or cross-fertilization.

Almost 15% of students thought that plants reproduce only by asexual methods: "some plants undergo budding, cutting and plants like algae undergo multiple fission process" (student 40); "Plants can not produce sperm and ovum" (student 111); "Plants do not have reproductive organs like animals" (student 23); or "Plants can not move to have sexual reproduction with another plant" (student 115). These responses show that the understanding of these students is largely guided by their knowledge of the process of sexual reproduction in animals.

Six percent of students thought that plants reproduce only by sexual methods: "Plants reproduce by the fusion of a sperm cell with an egg cell to form a zygote" (student 90) or "Because they involve both sperm and the egg and it has to combine sexually" (student 64). These responses again show their confusion of the reproductive systems of plants and animals. The rest of the students had no idea about an answer to the question.

One important observation was made after analyzing students' reasoning. It was found that only 15%–40% of students who ticked a correct choice were able to give scientifically valid explanations for their choices. This should be taken into account, given the recent trend of relying on multiple-choice objective tests, which are often used as the sole criterion on which student knowledge is judged. This study reveals that a significant portion (60%–85%) of students might not be really knowledgeable, even if they have selected the correct multiple-choice answer.

DISCUSSION

In an earlier study (Lewis *et al.*, 2000c) with middle school children in the United Kingdom, it was observed that 61% of students gave explicit views in the Cells section, compared with 46% in this study with Indian higher secondary school students. Both samples of students were found to have fragmented knowledge, which was incomplete and inconsistent in nature. They did not have a coherent view of cells, chromosomes, and genetic information within cells of the same individual. One of the reasons for such misconceptions, pointed out by Lewis *et al.* (2000c), was the teaching of these topics without linking related information to provide a "conceptual frame work." The results of this study also show that similar types of misconception persist even at higher levels of schooling. A majority of students were unaware of the nature of genetic information present in different types of cells within the same individual, and none could distinguish between somatic and germ cell (although some students could make the distinction in the study conducted in the United Kingdom).

A similar lack of understanding was also found in the Reproduction section, which showed different lines of thinking in the interpretation of the number of chromosomes in germ cells and the zygote. Students were confused about the relationships between genes, chromosomes, genetic information, and the cell, including such mistaken ideas as thinking that only germ cells carry chromosomes and that they are either X or Y types. Even though some students had a clear understanding of the subjects, the majority harbored widespread misconceptions.

In part 2 of the Reproduction section, most of the students related the sexual and asexual reproductive processes with environmental factors. Very few could recognize the importance of sexual reproduction in the process of evolution.

In responding to the types of reproduction in plants, students were largely guided by the mechanism of sexual reproduction in animals. None of the students used terms such as pollination or self- or cross-fertilization, for example. Like their responses to the question about the purpose of sexual reproduction in animal systems, students tried to link sexual reproduction in plants with environmental factors. Some students even felt that asexual reproduction takes place in lower plants, whereas higher plants reproduce only sexually.

With rapid growth in the field of genetics, considerable understanding of related subjects is necessary to grasp the importance and application of genetics and genetic technologies. According to Marbach-Ad (2001), "genetics instruction raises important political, economic, ethical and educational questions. Members of society must receive an effective education in order to appreciate these questions and their answers." As advocated by many science education researchers, students well versed in genetics and genetic technologies are able to understand trends in genetics research and the application of genetic technologies with regard to the social, legal, and ethical issues involved. However, understanding these emerging areas requires students to comprehend basic topics related to genetics, such as structure and function of cells, cell division, reproduction, and the process by which genetic information remains within cells and individuals and passes from cell to cell or generation to generation.

Lewis and Wood-Robinson (2000) found "widespread confusion, uncertainty and a lack of basic knowledge" among middle school children in the United Kingdom. This study reveals that students at the higher secondary level also do not have a clear understanding of genetic information in cells and its transmission during reproduction. As a follow-up study, it would be interesting to find out whether this lack of understanding is related to their understanding of the two types of cell divisions—mitosis and meiosis.

One reason for the lack of understanding by Indian students could be that the subject of biology, including genetics, requires only memorization of factual information—at both the school and college levels. Furthermore, teaching "low-quality content" also encourages only rote learning, without giving much importance to "higher order thinking" through problem solving. Even though teachers teaching at the higher secondary level are postgraduates in biology and those teaching at the secondary level are, at a minimum, graduates in biology (all of whom have had compulsory genetics educations at various levels), some teachers try to avoid topics like genetics because they are considered difficult to explain. Examinations, including those tied to the awarding of degrees at school and college (B.Sc.) levels, give students the opportunity to answer alternative questions drawn from other areas of biology and skip the difficult ones. In the present examination system in India, it is not compulsory to answer all of the descriptive questions (which are responsible for the bulk of the mark received by a student) included on a test. For example, students can answer three out of five questions given from different topics. Students are required to answer only the objective and short answer types of questions. Therefore, gaps in the teaching and learning processes are not reflected in the overall performance of the students.

Implications for Teaching Genetics

It is not yet clear at what level genetics should be introduced into the curriculum. As discussed by Marbach-Ad and Stavy (2000), arguments are given for its inclusion both before 16 (Deadman and Kelly, 1978; Engel Clough and Wood-Robinson, 1985) and after 16 yr of age (Shayer, 1974). Studies also have shown that difficulties in understanding genetics persist at school, college, and university levels (see Marbach-Ad and Stavy, 2000). These authors suggested that genetics concepts and processes belong to different levels of organization and are not often connected properly. Earlier studies by Lewis *et al.* (2000a, b, c) and Marbach-Ad (2001) showed that the concepts in genetics are "compartmentalized" and "without providing any conceptual frame work," which could be a result of teaching methodology. Classical and molecular genetics taught at different levels often are not connected properly, and the gap between the two remains an obstacle to the development of a holistic concept of genetics. Banet and Ayuso (2003) commented, "From an academic point of view, we consider it important to provide students with a basic conceptual framework for understanding the location, transmission and expression of hereditary information and the basic mechanisms involved in the evolution of living beings. Such knowledge would also help students to understand the biological significance of certain phenomena such as cell division, the reproduction . . . ."

Lewis *et al.* (2000c) presumed that time gaps between the teaching of related topics (e.g., cell division, life cycles, and inheritance) important for understanding genetic relationships are the main obstacles to building a "coherent conceptual frame work." Teachers, when teaching inheritance, should identify related ideas and draw them together so that students can develop further understanding of genetics and inheritance. The following ideas should be linked together for students: importance of chromosomes as organizers of genetic information; the physical entity of the gene; interrelationship between replication of the chromosome and genetic information; distinction between genes and genetic information; understanding that genes are switched on and off under different physical, developmental, and environmental conditions.

Various studies and the work reported here indicate that the teaching of genetics needs considerable review and strengthening. Because the abstract nature of genetics is difficult to conceptualize, other teaching aids—photographs, film and video, time-lapse phase contrast microscopy, models, etc.—could be introduced to explain the dynamic nature of the various processes, such as cell division (Brown, 1995). The emphasis in teaching and learning genetics should not be confined to covering the topics and having students memorize them by rote (which, by and large, is what is practiced in a majority of the schools and colleges in India, with some exceptions). Instead, genetics teaching should aim to instill conceptual understanding of the subject area and encourage thinking during the learning activities. Only then will students be able to assimilate and accommodate the related information in real-life situations.

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