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RESEARCH ON LEARNING

From Phenotype to Genotype: Exploring Middle School Students' Understanding of Genetic Inheritance in a Web-Based Environment

MICHELLE WILLIAMS, BERONDA L. MONTGOMERY, VIOLA MANOKORE

Abstract

Research shows that students face challenges as they learn about genetic inheritance. The challenges could emanate from the fact that genetic inheritance involves unseen processes at different organizational levels. We explored students' understanding of heredity and related concepts such as cells and reproduction using a Web-based Science Inquiry Environment (WISE) curriculum unit that was developed to help middle school students learn about genetic inheritance. Our findings suggest that students made significant gains from pretest to posttest. However, despite overall gains, some students struggled to explain the importance of mitotic and meiotic divisions in transferring genetic information.

Key Words: *Genetics; biological inheritance; student learning; middle school science; technology education.*

Scientists and science education researchers agree that genetics is an extremely important topic in today's society, especially for understanding issues such as genomics and genetic modification (Lewis & Wood-Robinson, 2000; Board on Health Promotion and Disease Prevention, 2005; Venville et al., 2005; Duncan & Reiser, 2007; Tsui & Treagust, 2007). For example, human genomics can help explain the causes of and responses to common chronic diseases that affect the health of a population. Simultaneously, genetics typically involves unseen processes at different organizational levels (e.g., proteins, genes, chromosomes, cells, and organs) and, as a result, genetics has been characterized as abstract. Consequently, many middle school and high school students (as well as college undergraduates) tend to find the topic difficult to learn (e.g., Stewart, 1982; Clough & Wood-Robinson, 1985; Moll & Allen, 1987; Bahar et al., 1999; Lewis & Wood-Robinson, 2000; Tsui & Treagust, 2007). Further, Venville et al. (2005) argued that although extensive research exists on secondary students' understanding of genetics and early primary students' conceptions of inheritance and kinship, research is needed on middle school students' understanding of genetics.

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Research shows that students often have considerable non-normative ideas about this topic even after instruction (e.g., Kargbo et al., 1980; Slack & Stewart, 1990; Banet & Ayuso, 2000; Lewis & Wood-Robinson, 2000). For example, many students believe that the genetic contributions of parents are unequal (e.g., that girls will inherit their mother's traits and boys will inherit their father's traits and that maternal contributions will be greater than paternal ones). These difficulties are likely related to the general problem that students have in understanding the underlying concepts of genes, alleles, and chromosome segregation that are central to understanding the heritability of genetic traits (Venville & Treagust, 1998; Banet & Ayuso, 2000; Lewis & Wood-Robinson, 2000; Wood-Robinson et al., 2000; Lewis & Kattmann, 2004). Other common misunderstandings include (1) difficulties in understanding the concept of the gene (Venville & Treagust, 1998); (2) difficulties in grasping how genotype differs from phenotype (Lewis & Kattmann, 2004); (3) uncertainty about the relationship between genes, alleles, and chromosomes (Lewis & Wood-Robinson, 2000; Wood-Robinson et al., 2000); and (4) difficulties in distinguishing between cell processes such as mitosis and meiosis, including how these processes are linked to the passage of genetic information (Lewis & Wood-Robinson, 2000).

Thus, drawing on the biological education research, Figure 1 depicts a model of how we conceptualize the relationship between genetic inheritance and cell division. This model delineates the connections between key concepts of distinct cell types and cell division, including both mitosis and meiosis, and underlying biological principles that are critical for an integrated understanding of genetic inheritance. The model also shows that genes and chromosomes are contained in all cells, the concept of dominance versus recessive alleles, the production of diploid mitotic products versus haploid meiotic products, and how a zygote results from the combination of cells derived from a female and a male parent during sexual reproduction. The model served as the basis for assessing whether students display an accurate

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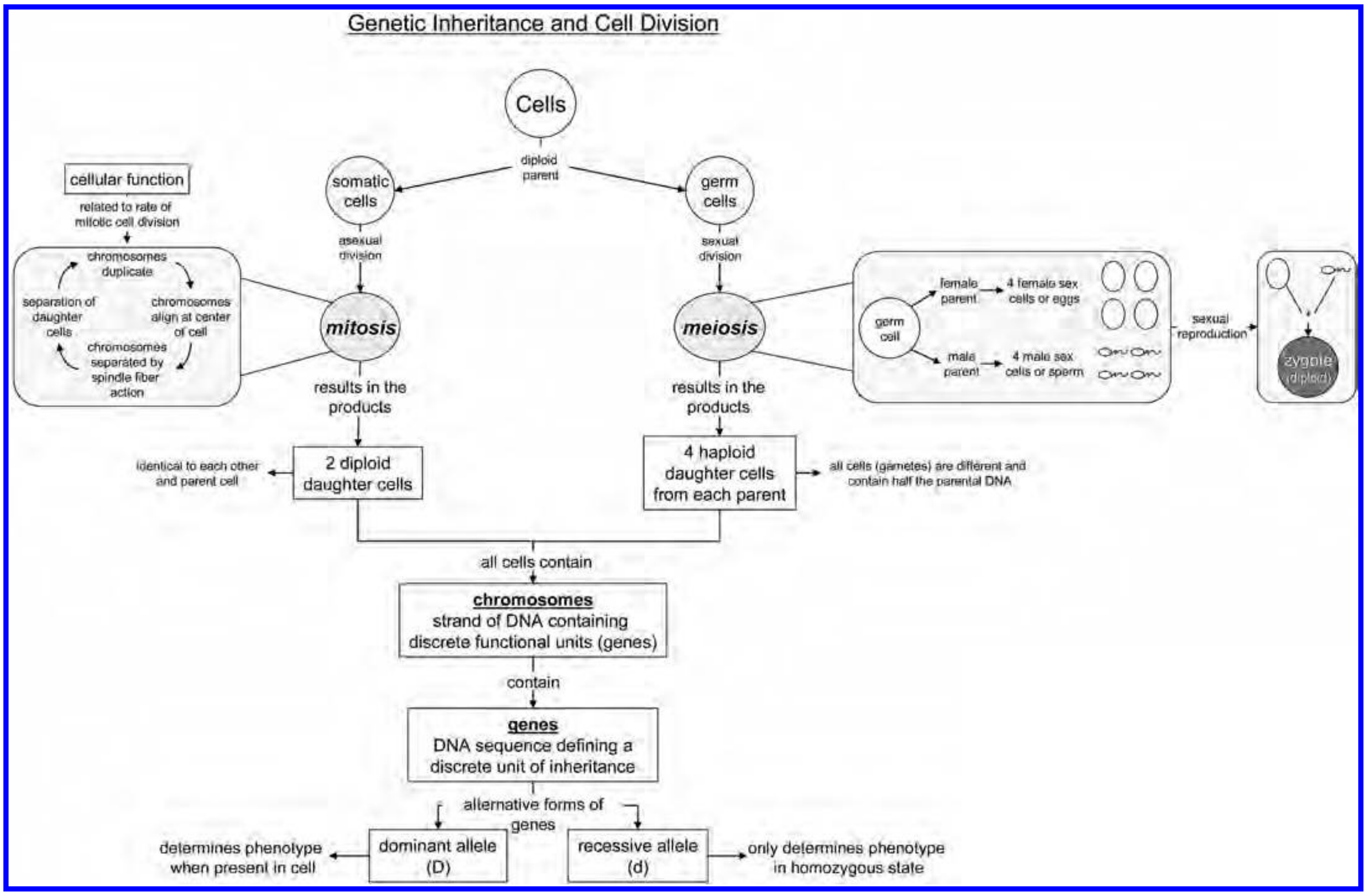

Figure 1. Model of the relationship between cell division and genetic inheritance.

understanding of cell division and genetic inheritance and to pinpoint where key misconceptions arise.

Technology-enhanced instruction has tremendous potential for promoting student learning around complex and abstract science topics such as genetics (Songer, 2006a, b; Tsui & Treagust, 2007; Roseman et al., 2008). For example, the Web-based Inquiry Science Environment (WISE) is a technology-rich learning environment that can scaffold and model inquiry with a navigation system, enable students to interface with real-world problems, and create opportunities for students to monitor and reflect on their learning process (Linn & Slotta, 2000; Kali et al., 2008). The present study explores the relationship between middle school students' understanding of genetic inheritance and their comprehension of cell division using the WISE Genetic Inheritance module.

○ Methods

Data reported here are part of a larger study designed to explore how upper-elementary and middle school students develop integrated understandings of heredity and related concepts within and across grades using both WISE and offline laboratory investigations.

This study was implemented in a suburban school district located in the Midwest within a socially and economically diverse community. The middle school, Pierce, from which the data were collected, comprises grades 7 and 8. There are two 7th-grade teachers at Pierce who teach science. Here, we analyze student data from ten 7th-grade classes that were taught by both science teachers. The total number of students who participated in the study is 209, including approximately equal numbers of males and females. The ethnicity of the entire middle school's student body was 7% Latino, 11% Asian, 28% African American, 57% Caucasian, and 1% Other. Pseudonyms are used to protect the identities of the school and the study participants.

WISE Heredity Materials

The WISE Genetic Inheritance module was designed by a multidisciplinary team of middle school science teachers, education researchers, biologists, and technology specialists. The present study was designed to help middle school students gain an integrated understanding of genetic inheritance through interacting with a Web-based environment and growing Wisconsin Fast Plants (Carolina Biological Supply, Burlington, NC) in the classroom. The students began the unit with a driving question: Who is the parent? At the onset of the study, the students were shown a photograph of one purple-stemmed parent plant but were not told that this parent had a dominant expression. The students were also shown the first generation of offspring that resembled the purple-stemmed parent in the photograph. They were challenged to unravel the mystery of parenthood by figuring out the second parent's phenotype and genotype for the stem color trait. The students grew the second generation of Fast Plants in the classroom. From the phenotype ratios of the second generation of offspring and using Punnett squares, they then determined the genotype and phenotype of the missing parent. By the end of the unit, having learned about Mendel's law of segregation and how genetic information is passed from parents to offspring, the students were expected to be able to answer "Who is the parent?"

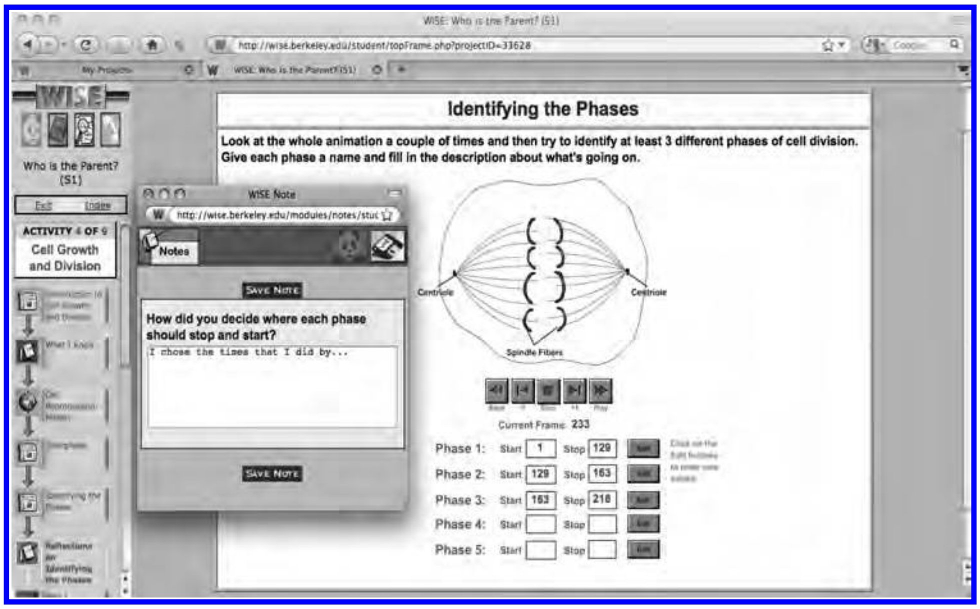

Figure 2. A screen picture of the cell-division visualization and embedded assessment in the genetic inheritance module.

Table 1. Summary of activities in the WISE Genetic Inheritance unit.

Activity	Description
Will You Help Us Solve a Mystery?	Introduces students to the curriculum unit and the overarching question for the unit – Who Is the Parent?
Inherited and Acquired Traits	Introduces "traits" as characteristics of organisms. Students distinguish between inherited and acquired traits of plants and animals.
Cell Structure and Function	Introduces students to the idea of cells as building blocks and that all living things are made up of cells. Students explore plant and animal cell visualizations as they learn about cell structure and function.
Cell Growth and Division	Introduces the process and function of mitosis. Emphasis is placed on the numbers of chromosomes in the parent and daughter cells.
Cell Differentiation	Introduces students to the concepts of multicellular and single-celled organisms. Students describe the hierarchy of cells, tissues, organs, organ systems, and organisms. They learn that different cells can divide at different rates through interacting with visualizations.
Sexual Reproduction and Meiosis	Students learn about sexual reproduction. They are introduced to the process of meiosis. Students are also asked to compare and contrast meiosis with mitosis. Punnett squares are introduced as students learn about determining genotypes and phenotypes of parents using second-generation phenotypic ratios.
Sexual and Asexual Reproduction	Students compare and contrast sexual and asexual reproduction. They interact with a visualization that enables them to decide the traits of two "sea monkeys," which are capable of reproducing either sexually or asexually and then create offspring from one or two parents.
Solving Our Mystery	Students determine which Fast Plant trait is dominant and which is recessive, including determining the genotypes of both offspring generations of Fast Plants. Finally, students are asked to determine both the phenotype and genotype of the missing parent plant.

WISE features an online inquiry map to guide students and support interactive visualizations. For example, Figure 2 shows an interactive visualization in the WISE Genetic Inheritance module to help students understand the different phases of mitosis. Other resources available to students in WISE include embedded assessments and online discussion forums. Table 1 summarizes the activities covered in the heredity unit.

Data Collection & Analysis

Assessment item development and validation.—The pre- and postcontent assessments included modified released items from state, national, and international science assessments such as the Michigan Educational Assessment Program, the National Assessment of Educational Progress, and the Trends in International Mathematics and Science Study. Some items were developed to assess the full range of knowledge and skills addressed in the instructional materials. To document the content validity of the assessments, two science-content and teaching experts rated the alignment of items and rubrics with the WISE curriculum activities and with the *National Science Education Standards* (National Research Council, 1996) and *Benchmarks of Science Literacy* (American Association for the Advancement of Science, 1993). Items and rubrics were also evaluated for scientific accuracy and grade-level appropriateness in terms of use of specialized vocabulary, reading load, and graphics.

Measures and analysis.—Identical pre- and postcontent assessment items were administered to 209 students. The assessment had 26 open-ended questions. However, for this study, we drew on 5 of the 26 items because of our interest in linking students' understanding of cell division to genetic inheritance. The pre- and posttest items were coded using a knowledge integration rubric adapted from Linn et al. (2006). Table 2 shows an example of an assessment item and rubric used to code the question (Q31), "Liver and skin cells are two types of cells in your body. Do you think they divide at the same rate or does one need to divide more frequently? Give an example to explain your answer."

Scoring.—The pre- and posttests were scored by three coders with

Table 2. Example of knowledge integration (KI) scoring rubric for question 31.

Score	Description of Generic Rubric	Example Student Responses
0	No response for the question.	Blank.
1	**Off task.** Student writes some text that is not relevant to the subject matter.	Skin covers the body and the liver is inside the body.
2	**No KI.** Students have isolated ideas. Ideas can be a mixture of normative and non-normative.	Skin divides more frequently than the liver.
3	**Partial KI.** Students provide normative ideas without elaboration or explanations.	Skin cells divide more frequently than liver cells because we grow and need more skin.
4	**Complex KI.** Scientifically complete and valid connections are made. Students provide an explanation for their answer.	Skin cells and liver cells do not divide at the same frequency. Skin cells divide more frequently because the skin is exposed and has to divide for growth and repair, unlike liver cells.

expertise in science content and teaching. The raters agreed on the scores for 90% of the students. Disagreements were resolved by discussions. A paired-sample t-test was used to analyze students' performance on the pre- and postcontent assessment.

○ Results

We assessed results from 209 seventh-grade students to determine whether linkages between cell division and genetic inheritance were being made using the Web-based heredity curriculum. Overall student performance on the WISE Genetic Inheritance module was significantly higher ($t = 25.11$, $P < 0.0001$) on the posttest than on the pretest. The overall gain was 26.89 and the effect size ($d = 1.78$) was large.

We conducted a detailed analysis on five assessment items designed to assess the connection of students' understanding of cell division and their understanding of genetic inheritance (i.e., Q8, 17, 23, 24, and 31). Findings show a correlation between the cell division processes (Q8, 17, and 31) and genetic inheritance items (Q23 and 24; Pearson correlation = 0.6; $P < 0.001$). When asked "What are the products of meiosis?" (Q8), the students provided answers that were, on average, considered off task in pretest responses ($M = 0.85$; Table 3). By contrast, the students showed significant improvement ($t = 11.77$, $P < 0.0001$) on the posttest, with a mean of 1.85 and large effect size of 1.217. An example of one student's progress is provided by comparing the pretest response of Student A, "The products are 4 cells, 3 new ones and they all can reproduce to create new cells," with the same student's posttest response, "4 daughter cells are the products of meiosis. The daughter cells have half the number of chromosomes as the parent." Despite overall gains, the posttest mean

Table 3. Descriptive statistics.

Question	Pretest (Mean ± SD)	Posttest (Mean ± SD)	Effect Size[a] (d)
Q8	0.85 (± 0.82)	1.84 (± 0.99)	1.217
Q17[b]	0.24 (± 0.55)	1.60 (± 1.30)	2.478
Q23[b]	1.00 (± 1.17)	2.10 (± 1.29)	0.933
Q24[b]	1.50 (± 1.44)	2.87 (± 1.25)	0.947
Q31[b]	0.68 (± 1.22)	2.89 (± 1.33)	1.813

[a]Effect size represented by Cohen's d (Cohen, 1988), with values >0.8 representing a large effect.
[b]Modified items from Linn et al., 2006.

scores suggest that some students lack knowledge integration about the products of meiosis.

A similar pattern was observed in overall pre- and posttest responses to items that probed the students' understanding of the mechanisms of mitosis. For example, the students were asked, "Imagine that spindle fibers did not form during mitosis but the cell still divided into two daughter cells. How might this affect the daughter cells? Explain your answer" (Q17). The pretest average of 0.24 indicates a very low level of understanding about the fundamental biological function(s) of spindle fibers and the process of chromosome segregation during cell division before students interacted with the WISE Genetic Inheritance module. Students' understanding improved significantly ($t = 14.13$, $P < 0.0001$) to an average of 1.60 on the posttest. For example, Student B responded that "I do not know what spindle fibers are, but I am guessing that the daughter cells might be deformed or they might malfunction" on the pretest, but answered "The daughter cells might not receive all of their chromosomes which might affect their functions if the cell divided and the chromosomes didn't get to the opposite sides of the cell because the spindle fibers didn't form, and the cell might not be able to divide at all" on the posttest. On average, findings from the posttest suggest that the students still experienced difficulty understanding the biological function of spindle fibers and the process of chromosome segregation during cell division. In order for students to more fully comprehend genetic inheritance, it is important for them to understand both how genes segregate during cell division and the functions of the products of meiosis and mitosis.

Besides understanding how genes segregate during cell division, it is also essential to understand dominant versus recessive alleles. When responding to the following question (Q23), "How is it possible for two parents with widow's peaks to have a child with a straight hairline?", students were largely off task ($M = 1.00$) in their pretest responses but showed highly statistically significant gains on the posttest ($t = 11.31$, $P < 0.0001$), though there still was a mixture of normative and non-normative ideas ($M = 2.10$). An example of students' progression is provided by Student C, whose response improved from "Because the genes from a different generation became dominant" on the pretest to "The child inherited a straight hairline from a previous generation" on the posttest.

A follow-up question (Q24) asked the students to demonstrate their understanding of recessive versus dominant traits using a diagrammed family tree. The students were instructed to find the genotypes of the parents and child, using a Punnett square to demonstrate how their answers were determined. The students exhibited a mixture of normative and non-normative ideas on the pretest ($M = 1.50$)

that improved significantly to a level of partial knowledge integration in posttest responses ($M = 2.87$). To answer this question correctly, students need only procedural knowledge because the correct representation in Punnett square form is a mathematical problem. No fundamental understanding of the biological mechanism of meiosis is required. By comparison, students had difficulty understanding how a homozygous progeny arises from two parents heterozygous for hairline trait, a question that requires a fundamental understanding of the processes and outcomes of meiosis, as exhibited in question 23 (refer to Table 4 for examples of two students' responses).

Another area that probed students' knowledge of the function of cells rather than requiring a deep understanding of the biological process of cell division was the correlation between cellular functions and rates of cell division. The question "Liver and skin cells are two types of cells in your body. Do you think they divide at the same rate or does one need to divide more frequently? Give an example to explain why" (Q31) investigates students' understanding of varying rates of cell division of different cell types. The pretest mean score was highly significantly different from the posttest mean score (Table 3; $t = 19.82$, $P < 0.0001$). The students improved from being off task to exhibiting partial knowledge integration. Indeed, among the five questions assessed, the students showed the largest gain (2.21) for this question. A sample student progression is represented by the responses of Student D: "I think skin cells divided more because there are a lot of skin cells than liver cells" on the pretest, compared with "The skin cells need to divide more frequently because it is often hurt or bleeding more than the liver's cells so that the skin cells need to repair" on the posttest. These findings, together with a detailed assessment of the written answers provided, indicate that the students progressed from non-normative ideas about the relationship between cell types and cell division rates to a more complete understanding about the relationship between cell division rates and functional differences between cell types.

○ Discussion

Although the students made significant progress on all questions, the smallest gains were observed for questions related to understanding of the products of mitosis and meiosis in terms of the amount of genetic material in daughter cells as compared with parent cells. The knowledge of cell division processes enables students to develop a deep understanding of genetic inheritance. However, the largest gains were observed in questions related to the use of a Punnett square to solve Mendelian genetics (Q23 and Q24) and to understanding the relationship between cellular functions and cell division (Q31). Our findings suggest that students can use a Punnett square in an algorithmic manner (e.g., Moll & Allen, 1987) without necessarily comprehending the meiotic division processes.

In fact, the greatest gain was for Q31. Note that the ability to provide an answer that shows complete knowledge integration for this question does not depend on understanding the process of meiosis, but only on understanding the relationship between cell functions and cell division. Also note that because meiosis depends on two rounds of segregation, students' lack of understanding of spindle fiber function carries over into continued misunderstandings about the process and products of meiosis. Indeed, we observed reduced knowledge integration in response to questions about the products of meiosis (Q8) and the process of chromosome segregation during cell division (Q17), even though significant gains were observed for pre- versus posttest for both questions.

On the basis of generalizations from the data, we propose that students' inability to master the concepts

Table 4. Example of students' responses.

<table>
<tr><th>Item</th><th>Pretest (Score)</th><th>Posttest (Score)</th></tr>
<tr><td rowspan="2">Q8</td><td>Student A. Products are 4 cells, 3 new ones; all can reproduce to create new cells. (1)</td><td>Student A. 4 daughter cells are the products of meiosis. The daughter cells have half the number of chromosomes as the parent. (4)</td></tr>
<tr><td>Student E. Blank. (0)</td><td>Student E. You end up with 4 daughter cells. (2)</td></tr>
<tr><td rowspan="2">Q17</td><td>Student A. Blank. (0)</td><td>Student A. This would affect the daughter cell by giving it two of one chromosome and none of another causing a mutation in the daughter cells. Since the spindle fibers pull the chromosomes apart and move them to opposite sides so that the cell may divide, if this did not happen the cells would not separate and therefore cause a mutation. (4)</td></tr>
<tr><td>Student E. Blank. (0)</td><td>Student E. Daughter cells may be deformed because I think the spindle fibers help the cell keep its shape. (2)</td></tr>
<tr><td rowspan="2">Q23</td><td>Student A. Blank. (0)</td><td>Student A. The mother and father must both have a recessive gene. The child inherited both of the recessive traits making them have a straight hairline. (4)</td></tr>
<tr><td>Student E. Child might not inherited that trait from either parents. (1)</td><td>Student E. The mom or dad's parents may have had a straight hairline causing the child to have one. (2)</td></tr>
<tr><td rowspan="2">Q24</td><td>Student A. Blank. (0)</td><td>Student A. Ww, Ww, ww. (4)<table><tr><td></td><td>W</td><td>w</td></tr><tr><td>W</td><td>WW</td><td>Ww</td></tr><tr><td>w</td><td>Ww</td><td>ww</td></tr></table></td></tr>
<tr><td>Student E. Ww, WW, ww. (2)<table><tr><td></td><td>W</td><td>w</td></tr><tr><td>W</td><td>WW</td><td>Ww</td></tr><tr><td>W</td><td>WW</td><td>Ww</td></tr></table></td><td>Student E. Ww, WW, ww. (4)<table><tr><td></td><td>W</td><td>w</td></tr><tr><td>W</td><td>WW</td><td>Ww</td></tr><tr><td>w</td><td>Ww</td><td>ww</td></tr></table></td></tr>
</table>

and fully comprehend the process of mitosis also impairs their understanding of meiosis. The process of meiosis initiates with a cycle parallel to the process of mitosis. Furthermore, an inability to fully understand meiosis is likely directly linked to students' inability to describe phenotypes arising from heterozygous parents. Although mitosis and meiosis are both cell division processes, their products are very different, which often confuses students (e.g., Q8). Mitosis results in daughter cells with the same genetic composition as parent cells, whereas meiosis results in progeny with different genetic composition from both each other and the parent cell (Figure 1). Furthermore, successful reproduction requires the combination of meiotic products from two different parents, ultimately resulting in a cell with a complex genetic make-up compared with the parent cells. These findings agree with those of other studies in suggesting that many students have difficulty understanding abstract concepts, including genetic inheritance (Slack & Stewart, 1990; Wood-Robinson, 1994; Lewis & Wood-Robinson, 2000; Kara & Yesilyurt, 2008).

Providing middle school students with opportunities to learn about cell division processes can enable them to develop more integrated understandings of the mechanisms of genetic inheritance. This can serve as a prerequisite for students' understanding of more complex genetics concepts such as multiple allele inheritance, topics included in high school and college genetics courses.

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