Students' Comprehension of Science Concepts Depicted in Textbook Illustrations

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Abstract

Visual representations are commonly used in science instruction to enhance learning. In this study, 86 high school biology students were asked to study an illustration of meiosis to determine their ability to recognize, understand, and interpret textbook images. Data collected from interview and written responses to questions revealed that while the task helped them learn about the topic of meiosis in terms of labeling structures and describing the phases, students were unable to communicate an understanding of the overall purpose of meiosis. The findings of this study have implications for the design and scaffolding of visual representations.

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Introduction

Historically, educational research has emphasized verbal learning while interest in visual learning has lagged behind. As the amount of information acquired through visual mediums multiplies, visual literacy, or the ability to understand, evaluate, and produce visual messages, has become increasingly important in education (Stanley, 1996). Specifically, considerable attention has been devoted to the effect of visual learning on the acquisition of knowledge and the understanding of relationships and processes in science courses (Mandl & Levin, 1989). Illustrations are the basis of visual learning in the science classroom and include representations found in typical science textbooks such as photographs, diagrams, charts, graphs, drawings, and tables. In a survey of six science textbooks, Mayer (1993) found that 55% of the printed space was accounted for by illustrations. Since illustrations are a large part of science textbooks, more attention must be focused on understanding the impact visual images have on students and their learning.

Visual presentations play a very important role in the communication of science concepts (Ametller & Pinto, 2002). Visual learning can foster the obtainment of knowledge that students may not get from verbal text alone (Mayer et al., 1996), and improve the retention of ideas presented (Newton, 1984). According to Lemke (1998, p. 110), "our visual discrimination is far better than our linguistic system at dealing with complex ratios and continuous variations in space, line, shape, and color." In science especially, visual images are preferred for displaying multiple relationships and processes that are difficult to describe. Thompson (1994) called thoughtfully designed illustrations "instructional obstacles," or devices that create a cognitive "hurdle" in the mind of the learner. These hurdles are necessary for learning and result from the construction of cognitive schemas where information is organized and linked together for storage in long-term memory. As the learner studies the details of the picture, s/he begins to overcome the cognitive hurdle. As a result, a fuller understanding of the concept is acquired. These hurdles do not hinder learning unless the visual is poorly designed; in that case, the illustration may easily overwhelm the learner's cognitive resources.

Unfortunately, not all illustrations will cause the same degree of improvement in comprehension and retention. Therefore, research on the impact of illustrations sometimes leads to contradictory results in which the value of illustrations is called into question (Thomas, 1978). Concepts can be represented pictorially in numerous ways and not all will be equally understood (Newton, 1984). As with verbal communication, illustrations have to be "read." In order to bring about more consistent improvement in knowledge acquisition, researchers have explored what factors enhance the readability of illustrations.

Textbooks make use of many types of visual displays to help teach difficult science concepts. Unfortunately, most textbooks also include decorative color photographs that are present more for selling purposes. Elaborate visuals, such as tables, diagrams, and flow charts that provide the bare essentials of a science concept, serve more to educate the student (Holliday, 1990). These summarizing visuals accent important relationships and reorganize information presented in printed text. They add clarity, and can segregate and group important information about difficult ideas.

Other research studies also indicate that the type of illustration could determine how powerful the illustration will be as a learning aid (Duchastel, 1978; Mayer, 1993). Mayer (1993) summarized four types of illustrations, modified from Levin's system of classifying illustrations. Mayer concluded that explanative illustrations, those illustrations with a verbal explanation that describe how scientific systems or processes work, elicit the highest level of cognitive processing. Other types of illustrations, like decorative color pictures, may not even affect cognitive processing. Most studies emphasize that a combination of both visual and verbal methods is ideal (Levie & Lentz, 1982). In one such study, visual-verbal learning had an additive memory effect over visual learning alone (Vasu & Howe, 1989). Visual-verbal learning allows students to reconcile the two modes and compare carefully the information available in the picture with the explanation in the text (Reid et al., 1983).

Other factors can affect what students comprehend from visual images. For example, different features of images affect the comprehension of the message transmitted by the image (Ametller & Pinto, 2002). The use of color, the use of arrows to display the flow of events, mixing of real and symbolic entities, highlighting of certain words or images, wording of verbal explanations, and integrating several images into one all have been shown to affect students' understanding of images (Stylianidou & Ormerod, 2002). Dwyer (1972) documented more difficulties in learning from realistic drawings and photographs than from simplified diagrams. He concluded that simple diagrams of the relevant structure were more beneficial because the important parts could be more easily viewed and identified while other details could be de-emphasized. Some students attach too much importance to artificial color in photographs and become confused when they see the real thing (Holliday, 1980). Mayer et al. (1996) found that the length of verbal explanation accompanying the illustration is also important. Short captions with simple illustrations are more effective than illustrations with lengthy verbal explanations. Contradictory results have been found about the ability of the learner and their understanding of visual images. Reid and Beveridge (1986) found that pictures with text were more distracting to some lower level students while other research indicates that lower ability students, who often struggle with verbal communication, benefit the most from visual learning.

More research on the factors that contribute to the readability of images is warranted, especially since studies have indicated that learners do not make full use of visuals in textbooks (Eshach & Schwartz, 2002). Many researchers have addressed whether students make the same sense of illustrations as experts do. Many expert readers, when tackling an academic article, "read" the visuals before the rest of the article. Novices may not understand how a system or process works from an illustration, while experts comprehend it easily and recognize the wider context (Goldsmith, 1984; Kozma & Russell, 1997; Kozma et al., 2000).

Although visual learning has received attention in the literature, much of the current research has focused on the visual representation of chemical phenomena (Kozma et al., 2000; Kozma & Russell, 1997; Wu et al., 2001). Very few studies concentrate on student learning from images typically found in biology textbooks. While computer-based multimedia instructional materials have become more prevalent, students' main exposure to visual representation is through textbooks. In this study, a visual representing the process of meiosis was utilized to determine students' recognition, identification, and learning from illustrations. Specifically, students were asked to study an illustration of meiosis and were then assessed on their ability to label the structures involved in meiosis, summarize the phases in meiosis, and give an overall summary of the purpose of meiosis.

The implications of the role of visual images in student learning are important. Visual images are a language and visual literacy can be learned, just as reading and writing are learned. Understanding the impact of visual images on viewers can be helpful with the design of illustrations in textbooks. In addition, educators in all disciplines at all levels can aid students in processing visual images more efficiently and in thinking critically about those images.

Method

This study was conducted to determine what students comprehend from a typical meiosis illustration. Data were collected from 86 biology students attending a suburban high school in the southeastern region of the US. A convenience sample of 47 students enrolled in freshman Honors Biology (two classes) and 39 students enrolled in senior Advanced Placement (AP) Biology (two classes) participated in this study. The same teacher taught all four classes using the same instructional methods. Although Honors Biology is the first science course these students take, they have had previous success in middle school science courses and on a placement test to be considered for this course.

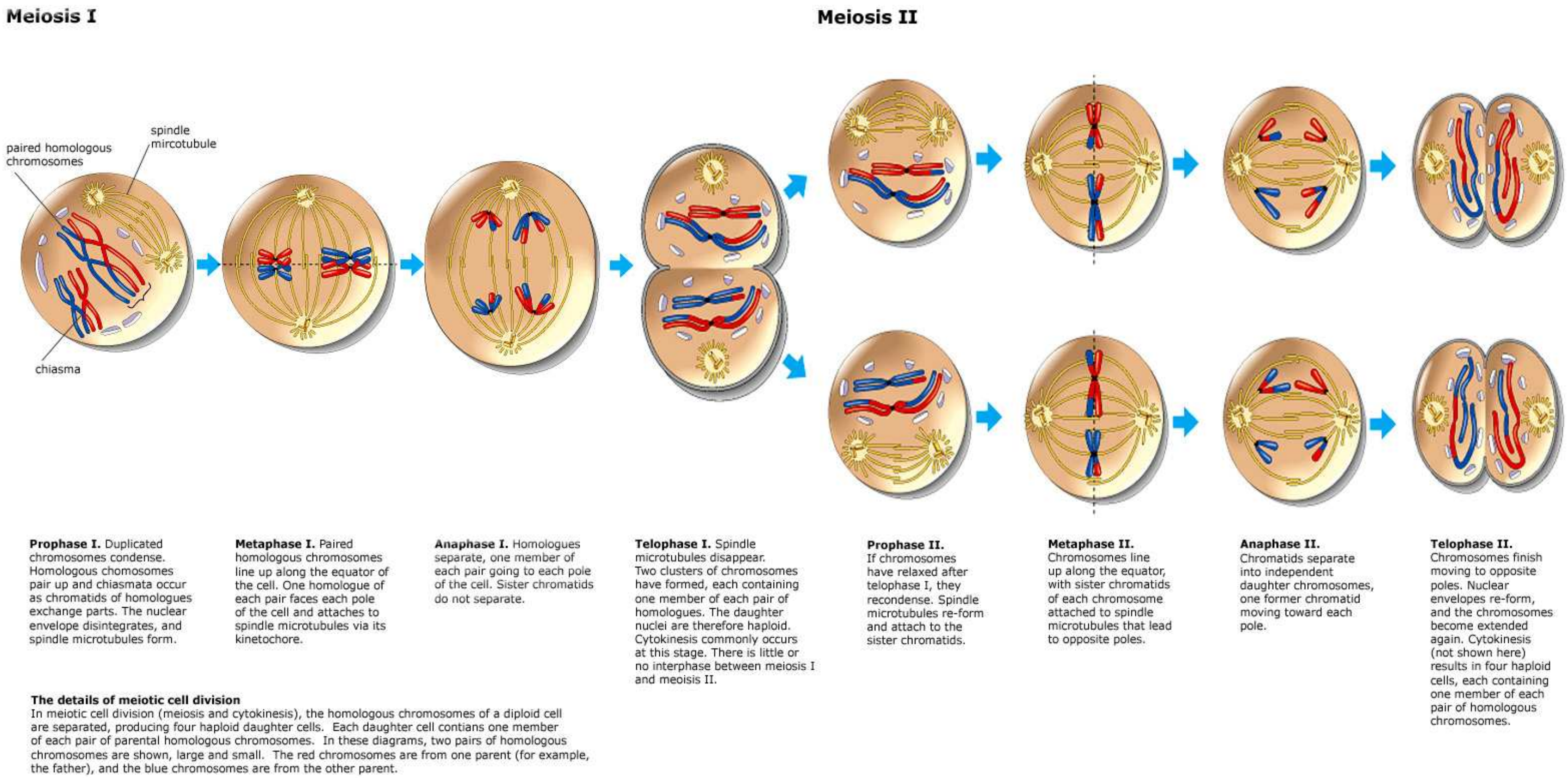

Figure 1. Meiosis illustration with accompanying verbal explanation (Campbell & Reece, 2002). (*Biology*, Cambell& Reece, ©2002. Reprinted by permission of Pearson Education, Inc.)

Students in AP Biology earned at least a B in previous biology and chemistry classes. Many of these students have previously taken or are concurrently enrolled in AP Chemistry or physics.

To familiarize the students with the concepts needed to understand the process of meiosis, they were taught the process of mitosis predominately through direct instruction. The teacher explained mitosis using visuals, and the students viewed the stages of mitosis through the microscope and participated in a group activity where mitosis was simulated using yarn. Following instruction on mitosis, students were presented a typical meiosis illustration (Figure 1) and asked to study the picture and the accompanying explanation. Students were asked to study the illustration for at least 10 minutes, but no longer than 20 minutes, in order to be able to answer questions about meiosis.

When students had completed their study of the graphic, they were given a handout with the same illustration of meiosis without verbal explanations (Figure 2). Students were asked to complete the following tasks:

1. Label the structures in the illustration.
2. Label the phases of meiosis and summarize what is occurring in each of the phases.
3. Give an overall summary of meiosis

Once the handout was completed, students were taught meiosis over the next three days. Similar to the direct instruction methods used while teaching mitosis, the teacher instructed the students by visuals and simulations with yarn.

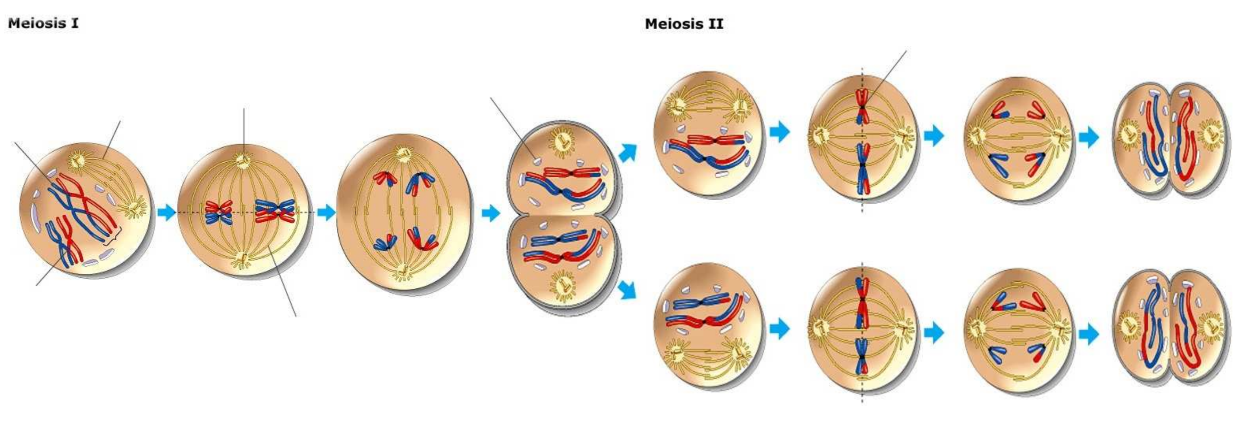

Figure 2. Meiosis illustration without accompanying verbal explanation (Campbell & Reece, 2002).

Following instruction on meiosis, 22 volunteers (10 AP Biology and 12 Honors Biology students) were interviewed. The following questions were asked during the interviews:

1. Are you aware of any errors you made on your handout or misconceptions you may have had before meiosis was covered in class?

2. When you were studying this illustration, did you look at the picture first or did you read the explanation first?

3. Were the structures depicted easily identifiable? Why or why not? How could this be improved to increase your understanding?

4. Were the various colors used in this illustration helpful in allowing you to better understand the process of meiosis? Why or why not? How could the color be improved to increase your understanding?

5. How helpful was the accompanying explanation to your understanding of meiosis? Did it give too much or too little detail? How could the explanation be improved to increase your understanding?

6. Overall, did the illustration aid in your comprehension of meiosis? Why or why not? Are there any other ways it could be improved to increase your comprehension?

Students' written responses on the handout were analyzed with a scoring rubric that identified students as having limited, marginal, or proficient understanding of the structures involved in meiosis, the phases of meiosis, and the purpose of meiosis. Students' ability to label the structures in the meiosis graphic was assessed, as well as which structures seemed to be the most difficult to identify. In addition, the detail in which students could recall the steps of meiosis was examined to determine if a particular concept was difficult to understand or completely overlooked. The ability of students to indicate the basic function of meiosis, as well as state ideas that were not directly described by the illustration or text, was also evaluated.

The responses from the interviews were analyzed using the constant comparative method (Strauss & Corbin, 1998). Initially, the data from each question were coded to develop categories; however, a key strategy was to constantly compare these categories. Categories that emerged were compared from one participant to the next, to allow for categories to be interrelated and refined, so that the patterns in how AP and Honors Biology students interpreted the illustration could be discovered (Hatch, 2002).

Findings

Labeling Structures

Relatively few errors were made in the labeling section of this task. As Table 1 indicates, 48.8 % of the students demonstrated a proficient understanding by identifying at least six of the seven structures correctly, while only 7.0% demonstrated a limited understanding by labeling five or more of the structures incorrectly. Most students were familiar with the terminology of meiosis from their prior experiences with mitosis. They had previously looked at pictures of mitosis and were able to identify the structures in mitosis illustrations. In their interviews, 12 students indicated that the colors of the structures helped in distinguishing between maternally and paternally inherited chromosomes. The structures most difficult for students to label were those involved exclusively in meiosis. Students struggled with labeling the chaisma and homologous chromosomes. Some tried to spell the unfamiliar word "chiasma," and it became apparent that they remembered what letter it started with and nothing else. Others could not remember the terminology of "paired homologous chromosomes" but instead used other descriptions like "exchanged DNA" or "reassembled chromosomes." In their interviews, many of these students stated that they understood what was happening in the process of crossing-over, but could not remember the terminology of the illustration. However, some students never even acknowledged the process of crossing-over, and instead labeled the structures with terminology from their prior background with mitosis. Instead of labeling the structure as chaisma, they labeled a portion of the structure a non-sister chromatid.

Table 1
Number (and percent) of AP and Honors Biology students who exhibit proficient, marginal, and limited understanding of the structures involved in meiosis

	Proficient Understanding	Marginal Understanding	Limited Understanding
AP	23 (59.0)	14 (35.9)	2 (5.1)
Honors	19 (40.4)	24 (51.1)	4 (8.5)
AP + Honors	42 (48.8)	38 (44.2)	6 (7.0)

Meiosis I Versus Meiosis II

Many students were able to accurately describe the steps of meiosis I and meiosis II, as shown in Table 2. These students with proficient understanding were able to describe the phases included in meiosis I and meiosis II in complete detail. Because they were familiar with prophase, metaphase, anaphase, and telophase from their study of mitosis, they were able to recall all of the pertinent information when writing out the process. They described chromosomes condensing, the formation of spindle microtubules, and attachment of the chromatids to kinetochores. However, not all students were able to incorporate the steps that were unique to meiosis or had difficulty describing all of the steps involved in a particular phase; these students were classified as having a marginal understanding of the phases of meiosis (see Table 2). For example, it appears as if some students never understood that homologous pairs of chromosomes segregate in meiosis I, whereas sister chromatids segregate in meiosis II. Therefore, if students had any misconceptions, it was almost always in meiosis I. Some students were vague about what was separated in anaphase I and wrote very generally that "chromosomes" segregated, and some recalled what they learned from mitosis and mistakenly wrote that sister chromatids separated. Regardless of mistakes made when labeling chiasma and paired homologous chromosomes, all but 17 students were able to indicate that chromosomes "exchanged sections" in prophase I. Only one instance existed where the student correctly labeled the chiasma in the labeling section, but then did not talk about its occurrence during prophase I.

Table 2
Number (and percent) of AP and Honors Biology students who exhibit proficient, marginal, and limited understanding of the phases of meiosis

	Proficient Understanding	Marginal Understanding	Limited Understanding
AP			
Prophase I	14 (35.9)	23 (59.0)	2 (5.1)
Metaphase I	12 (30.8)	26 (66.7)	1 (2.6)
Anaphase I	11 (28.2)	27 (69.2)	1 (2.6)
Telophase I	12 (30.8)	25 (64.1)	2 (5.1)
Prophase II	20 (51.3)	19 (48.7)	0 (0)
Metaphase II	24 (61.5)	15 (38.5)	0 (0)
Anaphase II	21 (53.8)	18 (46.2)	0 (0)
Telophase II	18 (46.2)	21 (53.8)	0 (0)
Honors			
Prophase I	12 (25.5)	31 (66.0)	4 (8.5)
Metaphase I	9 (19.1)	36 (76.6)	2 (4.3)
Anaphase I	8 (17.0)	36 (76.6)	3 (6.4)
Telophase I	10 (21.3)	34 (72.3)	3 (6.4)
Prophase II	14 (29.8)	29 (61.7)	4 (8.5)
Metaphase II	18 (38.3)	27 (57.4)	2 (4.3)
Anaphase II	21 (44.7)	24 (51.1)	2 (4.3)
Telophase II	16 (34.0)	28 (59.6)	3 (6.4)
AP + Honors			
Prophase I	26 (30.2)	54 (62.8)	6 (7.0)
Metaphase I	21 (24.4)	62 (72.1)	3 (3.5)
Anaphase I	19 (22.1)	63 (73.3)	4 (4.7)
Telophase I	22 (25.6)	59 (68.6)	5 (5.8)
Prophase II	34 (39.5)	48 (55.8)	4 (4.7)
Metaphase II	42 (48.8)	42 (48.8)	2 (2.3)
Anaphase II	42 (48.8)	42 (48.8)	2 (2.3)
Telophase II	34 (39.5)	49 (57.0)	3 (3.5)

Overall Purpose of Meiosis

All but 12.8 % of the students were able to indicate the basic function of meiosis (see Table 3). Those that wrote that meiosis produced four haploid cells from a parent cell were characterized to have at least a marginal understanding of meiosis. In addition to the production of haploid cells, if students understood that meiosis produces reproductive cells with genetic variation, they were considered to be proficient. Of those students with a proficient understanding, only five students stated that the reason why the four cells only contained half of the genetic information was because there is only one DNA replication in meiosis. Eighteen students stated that the purpose of meiosis was to make reproductive cells, but only seven students indicated that this process was restricted to the gonad region. Students with a limited understanding of the purpose of meiosis either stated that the resulting cells were identical or diploid.

Table 3
Number (and percent) of AP and Honors Biology students who exhibit proficient, marginal, and limited understanding of the purpose of meiosis

	Proficient Understanding	Marginal Understanding	Limited Understanding
AP	11 (28.2)	25 (64.1)	3 (7.7)
Honors	7 (14.9)	32 (68.1)	8 (17.0)
AP + Honors	18 (20.9)	57 (66.3)	11 (12.8)

Approach: Picture or Text First?

In the interview portion, 16 of the 22 students indicated that they viewed the picture of each step before they read the corresponding text. They visually accounted for the movement of the chromosomes and spindle microtubules, and then reconfirmed their visual analysis by reading the text. Only two students viewed all of the pictures first before they read the corresponding text underneath each picture. Four students tackled the illustration by reading the text underneath each picture first, and then ensured each picture showed what the text indicated.

Differences between freshman and AP Biology Students

The freshman biology students spent more time studying the meiosis figure. They utilized between 10 to 20 minutes studying the details of the visual whereas many of the AP Biology students were finished after 10 minutes. Since they were instructed to spend at least 10 minutes studying the figure, many of the AP students took out other work while waiting to receive the second part of the activity. In addition, the freshman biology students needed more time to identify the structures and describe the process of meiosis. Many of them required the remainder of the 45-minute period, while a majority of the AP Biology students were finished with 10 to 20 minutes left in the period.

The differences in the amount of time the different groups of students took to complete the task did not have an impact on their conceptual understanding of meiosis. The AP Biology students more accurately labeled the structures in the picture partly because their textbook explanation of mitosis was more detailed; 59.0% of AP students labeled at least 6 structures correctly compared with 40.4% of the Honors Biology students (see Table 1). The AP students were able to label the kinetochore and nonkinetochore spindle fibers even though they were not labeled on the illustration, while many of the freshman students were not able to make that distinction. In addition, the AP students more accurately wrote out the steps of meiosis. They were more likely to include all the events unique to meiosis; a higher percentage of AP students demonstrated a proficient understanding than Honors Biology students for each of the phases of meiosis (see Table 2). Finally, the AP students had a more complete description of the overall function of meiosis with 28.2% having a proficient understanding compared with 14.9% of Honors students (see Table 3). More AP students stated that this process made reproductive cells and was restricted to the gonads.

The AP Biology students asked questions after they were finished with the activity. These students wanted to ensure they accurately knew the details of meiosis and were more concerned than the freshman biology students to know if the answers on their papers were "right." Many of them asked the researcher to check the labeling of structures they may have had difficulty identifying. Some were concerned that their overall understanding of the process of meiosis was not complete enough. Others asked about specific steps of meiosis that were unfamiliar to them, such as crossing over in prophase I.

In the interviews, the AP students were less confident about their overall understanding of meiosis. Even though they labeled, portrayed the steps of meiosis, and gave the overall function of meiosis more accurately, they were less likely to believe they would have performed well on a test on meiosis. More freshmen students felt they would have performed adequately on an assessment than AP students.

Discussion

Overall Effectiveness of Illustration

Illustrations that depict biological processes have been shown to aid in the acquisition of knowledge and the understanding of biological concepts such as meiosis. Because the illustration used in this study was an explanative illustration, one with a verbal explanation of how a process works, it elicited a higher level of cognitive processing than a decorative color photograph would have. Every student interviewed indicated that the amount of verbal explanation supplied was important in his or her understanding of meiosis. Some students indicated that the color used in this illustration was helpful in identifying structures involved. As other researchers have found, attributes such as color and length of verbal explanation are important in fostering learning from illustrations. Finally, students in this study reconciled two modes of learning, visual and verbal, by studying the illustration and the accompanying text.

Most students interviewed felt like this activity helped them learn meiosis to an extent. Almost all of the students had a strong background in mitosis and knew much of the terminology. Almost all students verbally indicated in the interview portion that they would not have been able to label structures or list out the steps of meiosis unless they had that prior knowledge, since it seemed to them that the illustrations assumed prior knowledge. Five AP students missed the mitosis section due to an out-of-town field trip and one stated in his interview that he was not as confident about the labeling section. After viewing their answers, more mistakes were made in the labeling section, but many of them accurately detailed the steps of meiosis.

The results indicate that the students did not have too many misconceptions from studying the illustration, but they did not have a good foundation. They were fairly successful at labeling structures involved, listing the steps of meiosis, and indicating the overall purpose of meiosis. However, in their interviews, many students felt that even if they could recall the steps of meiosis, they did not feel as if they completely understood the whole process. They would have been able to detail what happens in each of the phases, party due to their prior knowledge, but they would not have been able fully incorporate all the unique aspects of meiosis. For example, several students knew crossing-over was occurring in the picture, however, they did not know why it was happening. Most students still wanted a verbal explanation from the teacher about how the chromosomes move and how genetic variation is introduced. Once they learned the process of meiosis through classroom explanations and activities, they were able to recognize their misconceptions in labeling and writing out the steps of meiosis, and understood more about the overall process of meiosis.

Most students recognized that this process was helpful. Even if they did not feel completely confident in their understanding, they realized that this activity served as a good introduction for learning meiosis in more detail. Some students indicated that when the process was covered in class, they related the new material learned back to what they wrote in this activity, and made connections. Even the student that continually claimed he was an auditory learner saw benefit to doing this activity. Many suggested that this process would be a good culminating activity for the unit.

The researcher expected to find that AP level students were more proficient at interpreting and learning from illustrations. In addition to having more prior instruction on the mitosis and meiosis, the AP Biology textbook covers these topics in more depth than the Honors Biology textbook. This prediction was confirmed by the results of the study; the AP students performed better on labeling structures, recalling the process of meiosis, and understanding the overall function of meiosis. However, the researcher did not expect the AP students to have more questions and need more reassurance about their level of understanding after the activity. From the researcher's classroom observations, the Advanced Placement students seem to be more independent than the Honors Biology students. Usually, they did not rely on the teacher as much for verification of the "right" answer and had developed a more "relaxed" attitude about learning. The researcher suspects that because there is not enough time to cover all topics and details in class, they are accustomed to learning independently. However, in this case, many of them did not feel comfortable about their specific understanding of the process of meiosis and were concerned that they were not going to receive any more clarification in class.

Limitations

The subjects of this research were high achieving, academically motivated students. They were Honors and AP Biology students who have been successful in their previous schoolwork. The results may have been different had a wide variety of students been sampled. Also, this study does not give any indication as to how helpful visual images are when learning a completely unfamiliar topic. Students had a basic understanding of chromosomes and mitosis before they were asked to study the illustration on meiosis. The study may have been more meaningful if it targeted how helpful illustrations are to students as they are covering the material in class. Instead, in this study, students were asked to look at an unfamiliar picture and label structures and steps in meiosis without any coverage of the material in class.

Implications

Visual representations play a critical role in the sciences, and the literature indicates that students may have more difficulty understanding them than initially assumed (Wu et al., 2001; Benson, 1997). It is important to study whether and to what degree students recognize the objects depicted in the illustrations (Constable et al., 1988). Teachers often assume students understand the visual images present in science textbooks. Student misconceptions in interpreting illustrations have been documented (Billings & Klanderman, 2000) and many stem from the lack of prior experience with the subject in their daily lives (Wu et al., 2001). Teachers must help students develop the basic skills of visual communication, specifically by teaching them to critically evaluate the form and content of visual communication. Students need to be taught how to read illustrations in order to avoid potential causes of confusion (Constable et al., 1988; Stylianidou & Ormerod, 2002) and teachers need to be aware of students' difficulties when reading images (Ametller & Pinto, 2002).

Many illustrations in textbooks depicting biological processes assume prior knowledge on the part of the student. Illustrators need to be aware that students may not have the background concepts they need in order to completely understand figures and tables commonly found in textbooks. They must present enough information in the illustrations to ensure student understanding. However, students also have difficulty identifying and understanding the concepts that unique to a particular process. Therefore, illustrators must be mindful of both what information they include to illicit students prior knowledge, and what information they include to foster comprehension of new concepts. Finally, they must pay careful attention to the colors used in illustrations, since many students interpret different colors to represent different structures.

Science teachers must organize the content in such a way that a student's previous knowledge can be used to acquire new knowledge. The sequence in which topics are covered should be planned with the intention to build upon the student's preexisting framework of concepts. Teachers must also emphasize the unique concepts related to a process and help students understand the relationship between this new process and what they have already learned. From this study, it is apparent that students cannot merely memorize structures and steps in a process and feel confident about their understanding of the process. Many students stated they needed a more complete understanding of "why" the steps were occurring. Therefore, illustrations can be used as a tool to aid in the comprehension of a process, but other tools should also be used for complete understanding.

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