Developing a Simulation Visualizing the Impact of Meiosis on Diversity

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Abstract

Computer simulations provide students the opportunity to observe and interact in realistic biological experiences. This designed simulation, “The Trio of Genetic Diversity,” made it easier for students to grasp the reasons for genetic diversity. During and after meiosis, the three processes (crossing over, independent assortment, and random fertilization) that occur are the primary sources of diversity. A separate module was designed for each of the three processes and presented in the order of occurrence. It will take three to five minutes for student to try each module. The simulation in this study was developed using Java programming language in the NetBeans IDE 8.2 development environment, along with the Swing GUI module. Java was used in the simulation so that it can be run easily in almost every operating system; furthermore, the interface is included in the Java library. The NetBeans IDE 8.2 software allowed the simulations to show the range of possibilities for genetic diversity. Chromosome images were created and converted into a transparent structure, and the coding process was started. The images and button actions in the simulation interface were carefully designed so that the user could understand them easily. This article introduces the simulation program and its features.

Key Words: simulation; meiosis; independent assortment; Mendel’s laws; random fertilization; crossing over.

Introduction

What is the reason for bridge collapse; how does a virus spread; why is the sky blue; and what are the bases of a stable ecosystem? These are some examples of the infinite universe of questions that can be explored by simulations (Repenning et al., 1999). Ton De Jong and Wouter Van Joolingen (1998) defined computer simulation as a program that contains a model of a system (e.g., natural or artificial equipment) or process. Students are not only motivated by simulations; they also interact with them and learn their reactions in realistic situations. In almost every situation, a simulation simplifies the truth by adding or changing details. In that simplified world, the student solves problems, learns procedures, and understands the characteristics of incidents and how to control them or realize various actions in different cases (Sahin, 2006).

Simulations take various forms, such as games, role playing, or an activity functioning as a metaphor. They can be used as a part of the learning process rather than as criteria outlining the subject. They encourage the use of critical and evaluative thinking. Because they are uncertain or open-ended, they encourage students to think about the effects of a scenario and also incite concept achievement through experiential practice. Simulations help students to understand the fine details of a concept. Students often find the activity more interesting than other activities because they experience it themselves instead of just hearing or seeing it (Bello et al., 2006).

The use of simulation is more advantageous than other visual technology products. For example, in video technology, students can observe complex, dynamic processes. However, unlike video technology, they can interact more with simulations and try all the alternatives of a process in simulation (Repenning et al., 1999). Researchers have shown that the use of materials that actively engage students is effective in helping them formulate scientific explanations (Baker & Moore, 1996).

For simulations to be scientifically useful, they should have a simple structure representative of the real world, based on actual events and data. Simulation studies should be run in real time to observe the parameters. A valuable aspect of simulations is that they can be infinitely repeatable, and they present the results after users try different variables. The instructor who makes the design can adapt the activity to the students’ skill level and to the number and needs of the students. Steps to be followed by students can be provided more easily online, or via notes in simulations (Blake & Scanlon, 2007). More emphasis is placed on the responsibility of the student who discovers learning through simulations.
Simulations can be used for learning and teaching in a new, technology-based learning environment (De Jong & Van Joolingen, 1998). Computer simulations are especially useful for posing laboratory works that are impractical, expensive, impossible, or too dangerous to carry out. Simulations can contribute to conceptual change, offer open-ended experiences, and provide tools for scientific research and problem-solving. Computer simulations also increase the potential for distance education (Sahin, 2006). In biology, physics, and social research in high schools, the use of digital computers and computer simulations is a good educational tool in supporting the curriculum and makes a great contribution to education (Visch & Braun, 1974). Yilmaz Kara (2018) reported that the development of learningware that can be used at higher education levels as well as primary and secondary education levels has a potential to provide positive results. He emphasized that to activate this potential, it is necessary to adopt appropriate software development processes and investigate the effects of the developed software comprehensively. It has been stated that in adult biology education, there is a need for further research on the impact of virtual laboratories and simulations (Hallyburton & Lunsford, 2013).

Simulation-supported teaching methods in biology are much more effective than conventional teaching methods (Sasikala & Tanyong, 2016). Therefore, our aim with this design study was to use the simulation technique to solve this basic meiosis problem that students often cannot understand and visualize. M. Reddy and Phyu Mint (2017) stated that in fact the use of animation-based, simulation-assisted strategic teaching methods is much more effective than the conventional teaching method in teaching genetic and DNA replication events. The use of simulation techniques for the presentation of basic biological principles has become widespread in recent years. Basic principles and concepts of biology can be learned easily with simulations.

Simulations can take the form of Java applications that can be accessed remotely through web browsers (Depenning et al., 1999). In the present study, Java programming language, which is commonly used in simulations, was used. In addition to Java applications, JavaBeans components that are freely integrated with other training components can also be used. Interactive simulations have great potential as communication tools to enhance the benefits of technology in education (Depenning et al., 1999).

Although meiosis is stated in related reference books as a type of division where chromosome number is reduced, it should be emphasized that besides its basic characteristics, diversity is responsible for the adaptation success of sexually reproducing species (Karatas et al., 2013). The simulation designed in this article is based on the meiosis teaching problem that students have difficulties in understanding. This problem has been made easier for students to understand using a simulation program. Moreover, a visual and interactive educational tool was obtained. This interactive simulation program was developed in a NetBeans IDE 8.2 development environment and simulated with the support of the Swing GUI (graphical user interface; button, label, panel, input area) of the Java programming language (Yildirim, 2019). The reason for using Java programming language is that it is easy to operate in almost every operating system, and the interface is included in Java’s structure. This software works in many operating systems (Linux, Windows, Ubuntu, and Mac OS) (Bozkurt, 2008).

The variation observed in populations depends on three separate processes occurring during and after the meiosis process (in order of occurrence):

1. Crossing over (in meiosis I during prophase I)
2. Independent assortment (in meiosis I during anaphase I)
3. Random fertilization (a random combination of male and female gametes during fertilization) (Campbell & Reece, 2008; Raven & Johnson, 1996; Russell, 2006).

Briefly, random separation of homologous chromosomes—formed in the anaphase stage of meiosis I—to the poles constitutes the basis of gametic diversity in species. Students express crossing over as a source of diversity in meiosis; it can be said that crossing over masks the function of independent assortment. Crossing over contributes to diversity by resulting in innovation in gametes. It is a source for diversity. However, the unusual aspect of crossing over is that it creates sources for diversity by forming a chromosome structure with a new gene arrangement that does not currently exist in the mother or father but only comes together during gamete formation. Therefore, it is important to correctly evaluate the contributions of independent assortment and crossing over to diversity and emphasize the different aspects of their effects on it. As a result, the diversity in the gametes that will form due to crossing over in prophase I and independent assortment (separation) in anaphase I increases, and this constitutes the source of the diversity in populations (Karatas et al., 2013).

Crossing-over possibilities were not taken into account in this study to emphasize the importance of independent assortment. Being a source of new gene sequencing, crossing over forms the source for diversity. While independent assortment forms the basis of diversity, diversity increases with the innovations that occur owing to crossing over. Crossing over is a new arrangement resulting from the mutual displacement of parts between the nonsister chromatids of homologous chromosomes (Campbell & Reece, 2008; Raven & Johnson, 1996; Russell, 2006). Thanks to this new arrangement, innovation occurs in the sequence of genes on the chromosome—two genes that are generally not present simultaneously in the individual. In other words, two genes in separate chromosomes in homologous chromosomes taken from the individual’s parents, namely two separate alleles, can come together owing to crossing over while the individual forms a gamete. This novelty generated by crossing over is a source for diversity, but it contributes to the diversity generated by independent assortment.

In other words, the basis of diversity is laid by independent assortment, and crossing over increases the contribution to this basis. However, in general, the concept of crossing over is perceived by students as the cause of diversity. This is one of the most common mistakes that I have encountered during my academic career. Asking the students the question “If crossing over does not occur, will diversity occur?” when explaining meiosis, they would either say no or give no answer at all. However, crossing over provides for novelty by mixing the characteristics from the parent that ultimately appear in an individual or one chromosome even though originally those traits were represented on different chromosomes. This important process should be emphasized as a novelty (Karatas et al., 2013). Previous studies also have reported that students had difficulty understanding the independent assortment due to which solution models were presented (Ruch, 1998). Research has shown that high school students have difficulty understanding meiosis and establishing a relationship between classical genetics (Wyne et al., 2010).

The primary purpose of this study was to render it easier for students, through a simulation, to understand the independent assortment and the probabilities that occur in the anaphase-I of meiosis, which is fundamental in diversity, and also to visualize
Mendel’s second law. Other processes contributing to diversity in sexually reproducing organisms (crossing over and random fertilization) were included in the simulation. The simulation was therefore named “Trio in Meiosis” by the researchers.

In the present interactive simulation study, to make it easy to understand, the number of chromosomes was increased. The whole process of meiosis providing diversity was integrated. By increasing the number of chromosomes to four, the result was easier to see. The other effects—crossing over and random fertilization—were added to the simulation, and the effect of variety in all aspects of meiosis was integrated.

The simulation was also performed in a pilot application, after which the students had the opportunity to express their opinion about its contribution to understanding the subject and ease of use.

**Methods**

**Development of the Simulation**

This interactive simulation program was developed in the NetBeans IDE 8.2 development environment and simulated by the Java programming language Swing GUI. Java programming language is preferred because it is easy to operate on almost every operating system, and the interface is within Java itself.

The design process of the simulation program took about six months. The project was started based on independent assortment, and crossing over and random fertilization processes were added to the simulation to understand all sources of diversity and also to provide a holistic approach (Yıldırım, 2019).

In this simulation, a species with four pairs of chromosomes were simulated to form gametes by meiosis. One of the reasons why the independent assortment is difficult to understand is that in books it is explained through images showing one pair of chromosomes. Therefore, the number of chromosomes was increased, and the study began with targeting seven chromosome pairs. However, due to insufficiency of the operating system and a problem fitting all the chromosome images on the screen, only four pairs of chromosomes could be used in the simulation (Yıldırım, 2019).

Next, images related to chromosomes were created and transformed into a transparent structure (Figure 1), and the coding phase was started. Care was taken to design the images and button actions in the simulation interface to allow easy understanding. During the development phase, the errors that occurred were tested and corrected by entering the program interface data. In the simulation of independent assortment and random fertilization, the possibilities were given in a specific order to prevent confusion and to allow students to see the resulting possibilities more quickly. The first state of the cell was also added to the left side of the screen to compare the probabilities that occur in the independent assortment process with the cell’s first state (Figure 2). The last stage of the simulation program focused on adding language support (Yıldırım, 2019).

**Independent Assortment Module**

Mendel’s law of independent assortment is based on the process of “Independent Assortment” in the anaphase-I phase. This process, which is also the primary source of diversity, is described in books with a pair of chromosomes, a representation that renders the possibilities difficult to comprehend. The chromosomes taken by an organism from its parents are mixed and distributed to the gametes during the independent assortment. This mixing and assortment occur in the Anaphase I stage of meiosis (Figure 3).

The number of gamete types that occur after meiosis is calculated by formula $2n$, but the independent assortment under this calculation cannot adequately represent the subject’s importance, as described in the books by a pair of chromosomal cells.

In this simulation, four pairs of chromosomal cells were represented. Accordingly, our representative organisms with four double...
chromosomes are likely to form $2n = 24 = 16$ (n: number of haploid chromosomes of the species) several varieties of gametes. The number 16 is the probability of a gamete variety occurring without crossing over. However, how can such a variety of gametes occur if there is no crossing over? The answer to this question is the independent assortment of homologous chromosomes in anaphase-I.

Explaining the simulation’s subject, we can say that an organism of a species with eight (four pairs) homologous chromosomes receives four of them from the mother and the other four from the father (Figure 4).

In anaphase-I, the individual's maternal and paternal chromosomes are randomly separated. The chromosomes shown in blue represent the ones coming from the father, and the chromosomes shown in red represent those coming from the mother (Figure 4).

So, while homologous chromosomes are separated from each other in this eight-chromosome organism, what will be the remixing and sharing of maternal and paternal chromosomes? To answer this question, the simulation was explained step by step.

With this simulation, it will be better understood how many possibilities humans or other organisms have during gamete formation and how only the independent assortment accounts for the variation in populations. Using the random fertilization module, students can easily see and understand how many possible gametes of the female and male are likely to pair.

**Crossing-Over Module**

Crossing over is a source of diversity (i.e., a source of new gene sequencing). While independent assortment forms the basis of diversity, crossing over increases the diversity through the novelties that occur. The crossing-over process creates a novelty through a new regulation (recombination) that occurs as a result of the mutual displacement of genes between the nonsister chromatids of homologous chromosomes (Campbell & Reece, 2008; Karol et al., 1998; Raven & Johnson, 1996; Russell, 2006). Two genes that are generally not found side by side in a chromosome of an individual are two genes in separate chromosomes in homologous chromosomes taken from the individual's mother and father; in other words, two characteristics can come together owing to crossing over while the individual forms a gamete. This event contributes to diversity by creating a novelty, a new gene sequencing. Crossing over is a source of diversity. However, the unusual feature of crossing over is that it forms a source of diversity by creating a chromosome structure that does not simultaneously exist naturally in the mother or father but carries a new gene sequence that comes together when creating gametes (Figure 5).

The possibility of diversity in the gametes that arises due to crossing over and independent assortment (separation) during anaphase-I in prophase-I is collectively observed in the simulation, as a result of which the source of diversity in populations is easier to understand. The part of the simulation so far explained is based on these two topics.

**Random Fertilization Module**

In the last step, the diverse gametes formed by independent assortment and crossing over are combined with random fertilization. Random fertilization increases the likelihood of diversity. Although the number of chromosomes is the same, the different gametes created by different individuals from different parents with different variations come together and increase the diversity. In the simulation, the chromosomes were represented by letters because all of them did not fit on the screen when indicated by chromosome shape, as in the other two modules. Representative heterozygous female and male individuals (AaBbCcDd) of these four chromosome pairs were used in the simulation. Eight representative letters, uppercase letters for dominant chromosomes and lowercase ones for recessive chromosomes, were used (A, a, B, b, C, c, D, d). The female and male individuals were represented by red and blue, respectively (Figure 6).

So far, instructions for the use of genetic information and simulation have been explained. To understand the contribution of this simulation to learning, a pilot study was conducted, the results of which are given hereafter.

**Pilot Study of the Use of Simulation**

In this part of the study, the pilot implementation of the simulation program prepared on the subject of meiosis and genetic diversity

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**Figure 4.** Representative chromosomes of an eight-chromosome organism originating from (1) the father and (2) the mother.

**Figure 5.** (1) Two pairs of chromosomes from the mother and father, (2) the next step button, and (3) the go-to-start button.

**Figure 6.** Representative heterozygous female and male individuals (Yıldırım, 2019).
was performed with last-year high school students studying in a public school affiliated with the Ministry of Education. After the application, 15 students were interviewed. Questions were asked to investigate the use and comprehensibility of the simulation. Below are the general results obtained from the student interviews.

- The meiosis triple simulation program has made it easier to understand genetic diversity.
- The application has made it easy to understand the causes of genetic diversity.
- The application has changed perspective on the subject.
- The application has explained the role of independent assortment in genetic diversity.
- The application was understandable and easy to use.

The results show that using the simulation makes it easier to understand the subject. We can also say that the simulation modules are easy to use, understandable, and practical.

**Discussion & Conclusion**

Simulations are exercises that can be used to enhance the effectiveness of teaching by encouraging active learning. They provide effective information acquisition, comprehension, implementation, analysis, synthesis, and evaluation. All of these elements contribute to an effective learning process in which cognitive skills are developed and applied. Simulations and games give students realistic experiences and enable them to learn concepts in a more meaningful way. The explanations related to the simulation activity encourage discussion and provide a background for analyzing situations in real life. Simulations and games have a strong impact on students because role-playing facilitates active learning and learning new concepts while enhancing student engagement, enthusiasm, and motivation (Zapalska et al., 2012). Braun (1971) stated that simulations were pedagogically useful (Braun, 1971). Simulations usually positively affect learning and teaching activities involving problem-solving (Mandinach, 1988). Simulations are useful in science education because they are effective in motivating students to learn with discovery (Laxman & Chn, 2011).

There is a limited number of studies using Java programming language, the one used in the present study. This may be due to the fact that pedagogues do not know Java programming language, and cooperation with other disciplines is not provided. Researchers suggest that Java should be used in teaching, but very few studies have been found. Kurtz and O’Neal (1998) developed a synchronicity simulator in their research titled “Developing Educational Materials in Java.” Therefore, it was suggested by Cavus and colleagues (2016) that it would be useful to incorporate programming language into the curriculum. In fact, because we could not find any exemplary work in biology education during this research, the necessity of learning this programming language in future generations has emerged. However, there may be many simulations that can feature cellular respiration, blood groups, gene cloning and other topics using Java programming language. Thus, collaboration between computer software experts and scientists will be useful.

Simulations and games give students realistic experiences and learning concepts in a more meaningful manner (Zapalska et al., 2012). In the pilot application conducted in the present study, students stated that it makes it easier to understand the subject and that the simulation is easy to use. New research with samples consisting of a greater number of students would be beneficial. The study substantiating this finding reports that using simulation-supported strategic teaching methods based on animation is much more effective than traditional teaching methods in teaching processes in genetic and DNA replication (Reddy & Mint, 2017).

The simulation developed in the present study has made the following contributions to the teaching of meiosis:

1. It renders the independent assortment, which is a process with results difficult to understand, easier to perceive.
2. Understanding the independent assortment also contributes to the understanding of Mendel’s laws.
3. The causes of the diversity that emerges in meiosis are expressed in an easily understandable form.
4. Since the main objective of this study was to develop and introduce a simulation program, a pilot application was conducted as a trial with a sample consisting of a small number of students. Further research with samples consisting of a larger number of students is needed to investigate the effect of simulation on learning.

This simulation is a starting point that can form the basis for new simulations. Suggestions in this regard are presented here:

5. It is recommended that, if possible, the three steps of the application should be opened on a single tab.
6. A more detailed program can be devised by preparing a simulation where representative alleles are placed on chromosome images. In this way, Mendel’s laws of independent assortment and the behavior of alleles in the independent assortment can be visualized.
7. Computer use and the Java program are required for this simulation. Since students actively use their mobile phones, a mobile application of the same simulation may be more useful. A research project to be conducted as a continuation of the present study could include developing a mobile application of the simulation.
8. In this study, the Trio of Genetic Diversity simulation program was developed. The original aim was to perform a simulation with 23 pairs of chromosomes, but the number of chromosomes was limited to 4 pairs by the operating system and screen size. The programming of this simulation could be further developed.

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