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Interactive virtual simulation as a pedagogical tool for learning natural selection in high school.

Simulação virtual interativa como ferramenta pedagógica para aprendizagem de seleção natural no ensino médio.

BEZERRA, Cíntia de Sousa[1]; SOUTO, Thiago Vinicius Sousa[2]

[1] 0000-0001-6769-7939; Instituto Federal de Educação Ciência e Tecnologia da Paraíba. Campina Grande, (PB), Brasil. cintia.bezerra@ifpb.edu.br.

[2] 0000-0003-0342-2746; Instituto Federal de Educação Ciência e Tecnologia de Pernambuco. Pesqueira, (PE), País. thiago.souto@pesqueira.ifpe.edu.br

A B S T R A C T

Studying natural selection in biology requires students to have the ability to abstract. Tools capable of simulating the evolutionary events of natural selection can help in understanding it. In this context, an interactive computer simulation was used in the teaching of natural selection. The research was developed with 40 high school students, using the simulation software known as PhET, available free of charge on the internet, which simulates population dynamics, genetic and environmental factors in successive generations of rabbits. The students received a script to carry out the simulation, then answered open-ended questions on the topic of natural selection. Based on the responses, a content analysis was performed as proposed by Bardin and the inferences and interpretations were made according to Ausubel's theory of meaningful learning. The responses were grouped into three categories: genetics, ecology and description. The execution of the natural selection simulation allowed the students to take a leading role, and their responses revealed evidence of meaningful learning, in which the previous concepts of genetics and ecology that had been studied previously emerged in the elaboration of the explanation of natural selection. The use of information and communication technologies, in this case specifically the use of interactive virtual simulation addressing natural selection, proved to be an important strategy to assist the learning process.

R E S U M O

Estudar o conteúdo seleção natural na disciplina biologia requer a capacidade de abstração dos discentes. Ferramentas capazes de simular os eventos evolutivos de seleção natural podem auxiliar na compreensão da mesma. Nesse contexto, uma simulação computacional interativa foi utilizada no ensino de seleção natural. A pesquisa foi desenvolvida com 40 estudantes do ensino médio, utilizando o software de simulação conhecido como PhET, disponível gratuitamente na internet, que simula a dinâmica populacional, os fatores genéticos e ambientais em gerações sucessivas de coelhos. Os discentes receberam um roteiro para realizar a simulação, em seguida responderam questões abertas sobre o tema seleção natural. A partir das respostas foi realizada uma análise de conteúdo conforme proposta por Bardin e as inferências e interpretações foram realizadas de acordo com a teoria da aprendizagem significativa de Ausubel. As respostas foram agrupadas em três categorias: genética, ecologia e descrição. A execução da simulação de seleção natural permitiu o protagonismo dos discentes, as respostas destes revelaram indícios de uma aprendizagem significativa, em que os conceitos prévios de genética e ecologia que haviam sido estudados anteriormente emergiram na elaboração da explicação de seleção natural. O uso de tecnologias da informação e comunicação, neste caso especificamente o uso de simulação virtual interativa abordando seleção natural, mostrou-se uma estratégia importante para auxiliar o processo de aprendizagem.

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Introduction

Contemporary education requires teachers and students to have an attitude of co-responsibility and self-management in relation to the learning process. In this sense, it is important that educational institutions promote didactic innovations that make learning meaningful, valuing students' prior knowledge. In recent years, science teaching has sought mechanisms that favor the improvement of teaching, in order to impact the civic and ethical formation of students, aiming at them being actors in the construction of knowledge and applying this knowledge, when it's necessary, in the most diverse scenarios in life (Ferri *et al*, 2015).

Possibilities of innovative methodologies, techniques and support materials are the great challenges that teachers encounter when using technological resources in schools, since these methodologies and techniques were often not part of their initial training. The use of simulation software is encouraged by the National Common Curricular Base (BNCC) for High School, being mentioned in 4 skills of specific competence 2 in the area of Natural Sciences (Brazil, 2018). This guideline indicates that the use of Information and Communication Technologies (ICT) can provide a way to innovate in classes, promote greater student engagement in teaching activities and consequent meaningful learning (Vieira & Silva, 2017).

Simulations can be used by students after school to review the content taught, as support activities for hybrid learning and any formal educational program in which a student learns, at least in part, through online learning, with some element of student control over time, place, path, and/or pace (Horn & Staker, 2015). Another application of virtual simulations guided by a script prepared by the teacher is in remote learning, in situations where the student cannot attend school due to maternity leave, health treatment, or even during a period of emergency remote learning such as that caused by the COVID-19 pandemic (Arruda, 2020).

The fact that scientific theories, such as biological evolution, have a high degree of complexity and considerable abstractions can constitute a complicating factor for both the teaching and learning of such concepts. This problem is researched in both elementary and high school education, therefore, adjustments in the teaching of Science and Biology are suggested (Brasil, 2018), which include the need to use several teaching resources, including technology. Leal *et al* (2019) identified that students in the 3rd year of high school presented a superficial knowledge of the concepts of genetics. One of the resources that can assist in the learning of complex and abstract content are computer simulations, as it is understood that these resources have the potential to assist in the understanding of concepts and processes in evolution and genetic aspects, in which students usually have learning difficulties (Lemos, 2020).

Natural selection is an evolutionary force capable of causing significant changes in the genetic structure of populations over generations. These changes are associated with the environmental adaptation that different variants of the same gene can confer on their carriers. Well-adapted descendants have a greater chance of reproducing and transferring these same alleles to the next generation. Therefore, it is expected that over time there will be a significant increase in the frequency of the most adaptive alleles and a decrease in those without these characteristics (Souza, 2008).

Approaching various topics in biology, especially those that have a certain level of abstraction, such as genetics, evolution, and natural selection, through computer simulations makes the content less abstract. By simulating interactions between prey and predator populations, it is possible to highlight the importance of genetic characteristics for the survival of the species, as these are processes that take a long time to be observed in nature, even experimentally, making them difficult to understand. In this sense, learning objects, such as computer simulation, bring the benefit of accelerating the visualization of consequences, by changing the causes related to these topics in biology (Cravo & Esparosa, 2020). In a simulation, genetic changes in generations of living beings, which would take years, happen in seconds, allowing the student to visualize these changes.

Many studies seek to include the use of computer simulations in science teaching, some of them based on the Theory of Meaningful Learning, formulated by Ausubel (Cardoso & Dickman, 2012). This theory seeks to understand the student's cognitive structure and, based on this, gradually present concepts, starting from broader concepts to more specific ones. Ausubel's studies focused mainly on a methodology contextualized with academic routine, which would be based on discovery learning, but without minimizing the importance of expository classes. For this author, meaningful learning is the most efficient human means to acquire and assimilate information in any area of knowledge (Lemos & Moreira, 2011).

The aim of this work was to investigate the potential of the interactive virtual simulation PhET (Physics Educacional Technology) as a pedagogical tool to facilitate the teaching and learning of natural selection with high school students, promoting student protagonism and analyzing evidence of significant learning in the relationships that students establish between the scientific concepts of natural selection and the events observed in the simulation.

Methodology

This study uses an approach using qualitative research methods that seeks to deeply understand the social group studied, producing detailed and illustrative information, whether on a small or large scale. It can use numerical data without being restricted to quantitative models to understand phenomena and draw inferences (Poupart *et al*, 2008).

General characteristics

The research was developed with 45 students, between 16 and 18 years old, from two classes of Integrated High School and Technical Education at the Instituto Federal da Paraíba (IFPB). The classes were from different technical courses but had the same subjects of the common base, among them the subject biology in which the sequence on natural selection was developed. The sequence was carried out from April 21, 2021 to May 22, 2021, as part of the 4th academic semester of 2020. The delay in the academic calendar was due to the COVID-19 pandemic.

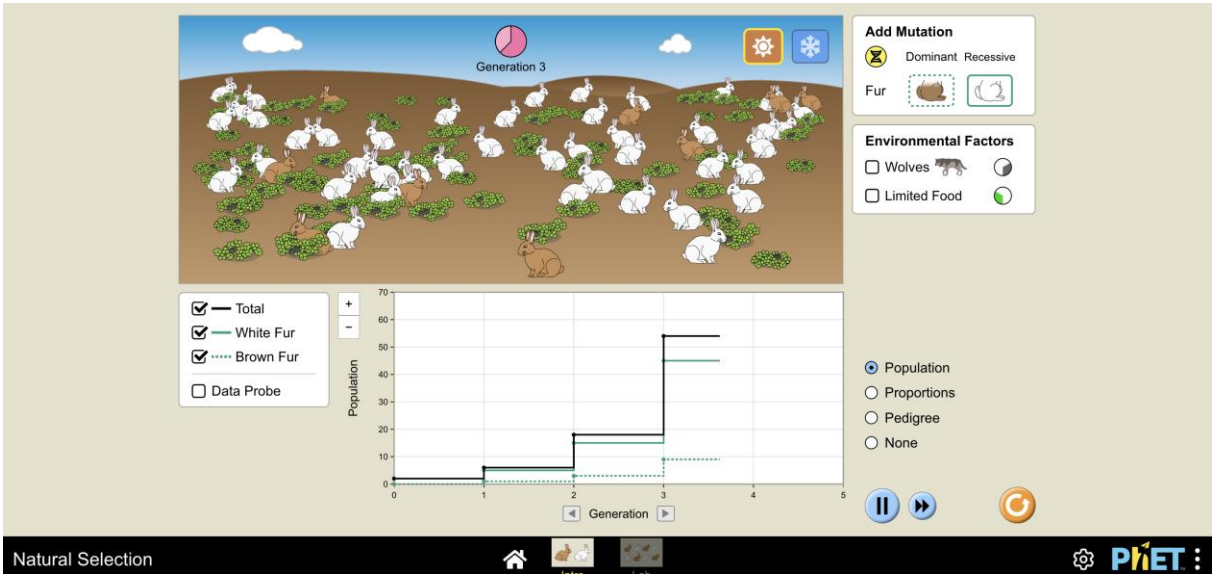
All classes were held via Google Meet and recorded with verbal authorization from those present. The course meetings took place once a week, for 1 hour and 30 minutes. Four meetings were held to execute the sequence. The students were 60% female and 40% male, half lived in Campina Grande and half in neighboring municipalities, most of them in urban areas, with 13 students living in rural areas, which limited their internet connection.

Simulation description

The learning object (computer simulation) used was the simulation software known as PhET, a project associated with the University of Colorado (USA) and designed by Carl Wieman, winner of the 2001 Nobel Prize in Physics. PhET offers simulations in a wide range of areas such as Mathematics, Physics, Biology, Chemistry and Earth Sciences and can be used from Elementary School to Higher Education. The simulations are available free of charge and can be used online or downloaded for offline use (Figure 1).

Figure 1.

Computer simulation of natural selection available on the University of Colorado's PhET



website *Note*: Macgarry (2021)

The natural selection simulation available on the PhET Interactive Simulations website is an interactive educational tool that allows users to explore how natural selection acts on populations over time. The simulation is designed to be intuitive and visually engaging, facilitating the understanding of fundamental concepts of biological evolution. It begins with a virtual environment where a population of rabbits lives that have different characteristics determined by their dominant or recessive genes, such as fur color, tooth size and ear type.

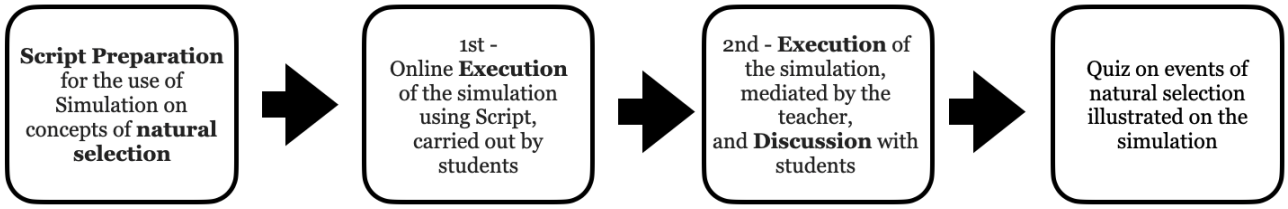
The user can adjust environmental factors that act as selective pressures, such as the presence of predators, food availability, and seasonal changes, which can affect survival. Surviving rabbits are given the opportunity to reproduce, passing on their traits to the next generation. Over several generations, it is possible to observe how the frequency of traits in the population changes in response to selective pressures (Macgarry, 2021).

The simulation provides real-time graphs and data showing changing trait distributions and population sizes, helping users visualize and analyze effects of natural selection quantitatively.

Development of the teaching sequence

Initially, a script was developed to explain the simulation step by step. After verifying the students' autonomy, the first moment was asynchronous, in which the effective exploration of the simulator was proposed, to maintain the focus on exploring the content. Students had a period of one week to carry out the simulation before the synchronous class. During the synchronous class, how to manipulate the virtual experiment was demonstrated and the students were able to express their doubts and difficulties (Figure 2).

Figure 2



Steps of the teaching sequence using the virtual simulation on natural selection

Note: Own authorship

The activity was assessed using a questionnaire with specific discursive questions about the experiment data and concepts. The selection factor suggested in the script was the inclusion of wolves to prey on the rabbits; the student was free to choose how many times the predation would occur, which would directly affect results. There was also a suggestion to use another alternative “selection factor” that predicts the availability of food and the size of the teeth as a variation among the rabbits. This suggestion was not mandatory, but it helped to determine which students would be more curious and exploratory. The questions were:

1. After the wolf predation, how many rabbits of each color survived? What can we conclude from this data? Explain based on Darwin's theory.

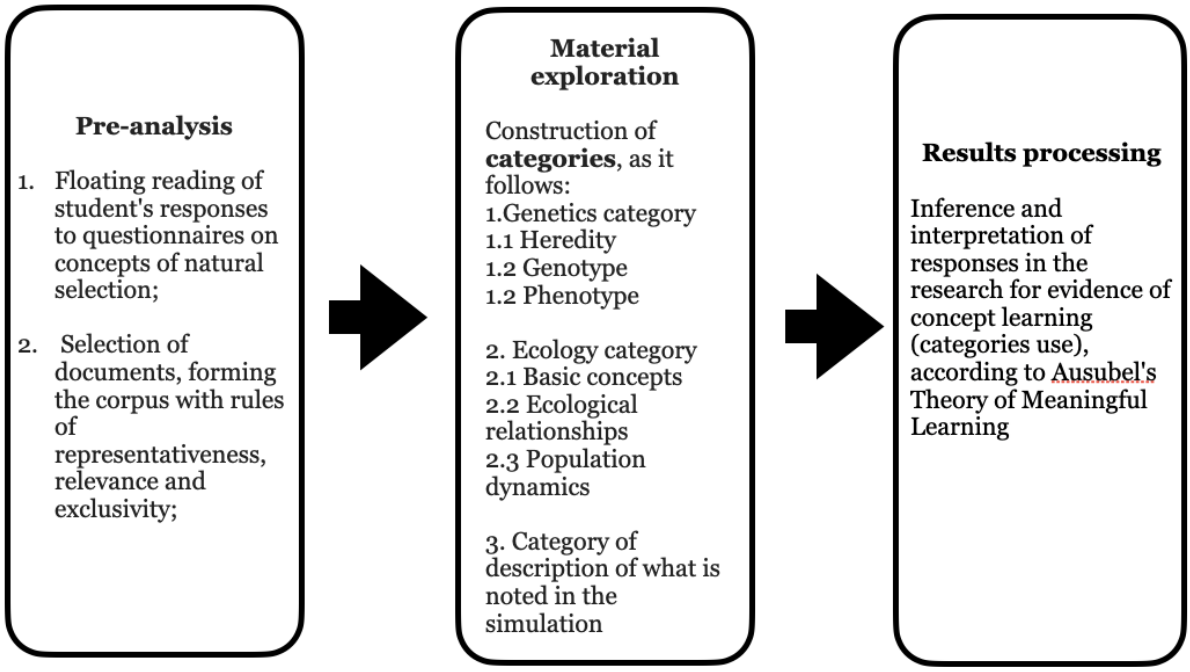
2. Did the environment favor the survival of the rabbit population?

Students submitted their quiz answers through a Google Classroom activity.

Content analysis

In order to deep and investigate responses of these students in the assessment stage of the teaching sequence, the Content Analysis proposed by Bardin (2011) was used (figure 3). Thus, a pre-analysis of responses written by students was initially carried out by skimming them. Based on the skimming, questionnaires that would form the corpus of the research were defined. The corpus is the set of documents that will be submitted to analysis and its constitution implies choice, selection and rules (Bardin 2011). The selection of questionnaires that made up the corpus followed the rules of representativeness, because even with the exclusion of 5 questionnaires, the 38 documents chosen represented the students. The questionnaires that were excluded from the analysis were plagiarized, therefore they did not correspond to the objective of the study, which was to verify the signs of learning, and therefore did not follow the rule of relevance. Following the rule of exclusivity, an element should not be classified in more than one category. Thus, responses were classified into categories and subcategories according to the predominant theme in the response, as some of them involved more than one theme.

Figure 3



Steps of content analysis of student responses

Note: Own authorship

In the material exploration stage, the corpus was studied in greater depth with the aim of establishing the registration units and context units. According to Franco (2008), the Registration Unit is the smallest part of the content, whose occurrence is recorded according to raised categories. Records can be of different types that may be interrelated: the word, the theme, the character, the item. In this study, the theme was established as the registration unit.

The last stage was data processing, inference and interpretation. Data analysis in this last stage was based on Ausubel's (2003) theory of meaningful learning. Discussions of the results occurred after the emergence of categories that were the interpretations of the data. In this study, the categories emerged after content analysis, since they were not defined firstly (BARDIN, 2011; FRANCO, 2008).

Results and Discussion

The simulation allowed the investigation of different situations. The initial situation proposed in the script was of brown and white rabbits in a summer environment with wolves as predators, where students controlled when wolves attacked. The simulation allowed the students to investigate the proposed situation, elaborate explanations for causes of predation of rabbits with brown fur on sandy terrain, it was possible to exercise curiosity by changing the selection factors and verify different results that these caused and also communicate their conclusions based on the analysis of the data obtained that varied for each one due to the way in which they executed the simulation. These skills worked on when executing the simulation and answering the questionnaire are addressed in the National Common Curricular Base (BNCC), especially in the general competency of basic education number 2 (Brazil, 2018).

Of the students, 38 completed the activity and submitted their questionnaire responses, 34 within a week before the synchronous meeting and four after the synchronous meeting. Two chose to perform the alternative activity of creating a conceptual map because they were unable to perform the simulation due to limitations on their cell phones. After students interacted with the virtual simulator, we sought to understand the influence that the learning objects, in this case the interactive simulations, had on the participants' learning motivation. For Moran *et al* (2013), digital technologies, which enhance the use of active methodologies, can contribute to the development of students who are more active and responsible for their learning.

Regarding motivation, through the debate held in the synchronous meeting after the activity, enthusiasm was clear. However, the influence was not limited to enthusiasm. Despite there being a script that guided the use of the simulator, at various times the students sought to explore other available resources, such as changing the other factors and selection available in the simulator, but which were not in the script. As Freire (1983) points out, knowledge requires a curious presence of the subject in the face of the world. Thus, they assumed a more active and protagonist role that is fundamental for the construction of knowledge.

The student's protagonism includes their active participation in learning, the ability to make decisions and the ability to solve problems autonomously (Azeredo & Jung, 2023). At the first moment of executing the simulation on natural selection, students had the freedom to decide when and how many times they would release predatory wolves as a factor of natural selection, they could also choose whether or not to change the food and climate limitation factors.

According to Ausubel (2003), in discovery learning, the learner must first discover this content, creating propositions that represent solutions to the problems raised. Alternative situations presented by the simulator were snowy environments in which a decrease in the population of brown rabbits was observed, which allowed a debate about camouflage. There was also the option of not including predators but using food limitation as a selective factor and long or short teeth as variability. Twenty students used the snowy environment in addition to the situation proposed in the script. Three students used food as an alternative situation to that proposed by the script. In this way, students created new problems, observed and analyzed their consequences, and developed possible explanations based on what they had previously studied.

The Content Analysis methodology was applied to students' responses and three thematic categories emerged: the Genetics category with the subcategories heredity, genotype and phenotype, the Ecology category with the subcategories basic concepts, ecological relationships and population dynamics and the Description category without subcategories (table 1).

In the third and final stage of content analysis, data processing, inference and interpretation, responses were analyzed based on Ausubel's (2003) theory of meaningful learning. Assuming that the use of the natural selection simulation, as potentially meaningful material, would allow the development of superordinate learning in which the potentially meaningful concept (in this case the concept of natural selection) would be more general and inclusive than the concepts already established in the cognitive structure, such as the concepts related to the contents of ecology and genetics.

Table 1.

Categories and subcategories that emerged from students' responses to the question "After the wolf predation, how many rabbits of each color survived? What can we conclude from this data? Explain based on Darwin's theory." Followed by the number of students' contributions and an example of the speech.

Category	**Subcategory**	**n**	**Speech example**
Genetics	Heredity	4	" the **characteristic** of the white coat **is passed** on to next **generations**"
	Genotype	2	"... and by its **recessiveness**"
	Phenotype	2	"survived by **physical characteristics**"
Ecology	Basic concepts	4	" This is due to the **food net**"
	Ecological relationships	14	"all brown-coated rabbits survived **predators...**"
	Population dynamics	2	"...in the continuity or **extinction** of a given **population** lineage"
Description	-	10	" in the end, there were 2 white rabbits and 25 brown rabbits"

Note: Own authorship

Genetic concepts most cited by students in their responses were phenotype, genotype, genetic variability, heredity and mutation. Ecology concepts were camouflage, predation, herbivory, overpopulation and species extinction. Genetics and ecology contents had already been studied by the students in the two semesters prior to the simulation. Thus, it can be seen in the responses that students were able to combine these previous concepts in the interpretation of the simulation performed. The recombination of these previously existing elements in the cognitive structure is referred to by Ausubel as integrative reconciliation, and is one of the processes that occur during meaningful learning (Moreira, 2006).

The subcategory with the highest number of contributions was predator, with 14. The term predator was frequently cited directly and indirectly in most responses, but due to the rule of exclusivity in content analysis, an element should not be classified in more than one category. The presence of this concept in students' responses indicates that this may be one of aspects of the existing cognitive structure that is most relevant to new, potentially significant material. According to Ausubel (2003), this prior knowledge is the determining factor in the learning process.

In the population dynamics subcategory, two students reported observing rabbit overpopulation due to the low number of wolf attacks imposed in the simulation, another student imposed so many wolf attack events that it led to the extinction of rabbits. Responses of these students highlighted population dynamics as a relevant factor in natural selection.

Among responses, 28 students were able to answer questions proposed in the script correctly through the simulation. Six of them, in addition to answering, made a direct connection with neo-Darwinism. The Synthetic Theory of Evolution or Neo-Darwinism includes Population Genetics to explain evolutionary processes. In it, evolution can be explained by mutations and genetic recombination, guided by natural selection (Souza *et al*, 2011). In this way, the neo-Darwinian theory itself combines the concepts proposed by Darwin with the genetic concepts of mutation and genetic recombination that were not found in Darwin's theory. The relationship between Darwin's theory and the Synthetic Theory of Evolution made by students gives evidence of an integrative reconciliation. Integrative reconciliation from an instructional point of view is referred to by Ausubel (2003) as a principle according to which instruction should explore relationships between ideas, point out important similarities and differences, and reconcile real or apparent discrepancies.

The second question (Table 2) aimed to encourage students to understand the influence of the environment on changes in the rabbit population. The Ecology category received the largest number of contributions. In responses of most students, the concept of camouflage appeared explicitly in various contexts.

The concept of camouflage stood out probably because it was well illustrated in the simulation; when a concept is represented in an image, it becomes more concrete. One student, in addition to commenting on the camouflage observed in the simulation, related it to the camouflage that occurs in snakes that live in the Caatinga, the biome where the student lives. This relationship can be explained according to Ausubel (2003) through the anchoring of new knowledge in concepts that already exist in their cognitive structure.

Table 2.

Emerging categories from the question “Does the environment favor the survival of the population?”, number of students who contributed to this category and examples of speech.

Category	n	speech example
Genetics	2	" considering that the brown skin **mutation** favors the survival of species"
Ecology	26	" brown rabbits are **camouflaged** and white rabbits are more visible"
Description	10	" all white rabbits were eaten by the wolves and the brown ones survived"

Note: Own authorship (2024)

In this second question, the genetic category received only two contributions. Only two students highlighted the mutation in fur color as a factor that favored the survival of species. Even though, in the simulation, the mutation favors camouflage in the environment, this relationship was not explicit in the answers of these students.

Leal *et al* (2019) when researching genetic knowledge in high school students found a superficial knowledge of this content. Teaching Genetics in high school is considered one of the most challenging curricular components for students to understand (Thörne, 2013). Overcoming this situation is a challenge for scientific and biological education, not only to train new scientists, but also to ensure that individuals have a critical approach to biological content (Leal *et al*, 2019).

A third category emerged after the analysis, the "Description" category. This category received 10 contributions in both first and second questions, and was identified as description, since responses of this group of students were limited to describing what they observed in the simulation without making any interpretation. In other words, they were unable to develop answers that evidenced significant learning. For students to learn Biology, including natural selection, it is necessary to overcome many difficulties such as developing cognitive flexibility and various information processing skills (Eilam and Reiter, 2014). In the absence of these skills, mistakes arise and memorization prevails in order to pass the school grades, resulting in a superficial understanding of each content (Tardif & Lessard, 2014).

This type of response would be best explained by rote learning, in which the new information will have little or no association with existing relevant concepts (Lourenço *et al*,

2012). This learning also occurs literally, the student learns exactly as it was spoken or written, with no room for their own interpretation. Learning occurs as a product of the absence of prior knowledge related and relevant to the new knowledge to be learned. However, concepts learned rote can become much more meaningful as knowledge expands (Braathen, 2012).

This result showed that interactive computer simulation, like any other information and communication technology applied to teaching, does not ensure learning when used without guidance. The teacher must act as an organizer and mediator, presenting problems linked to everyday life and valuing students' prior conceptions to promote meaningful learning of fundamental concepts (Sampaio, 2017). Cravos and Esparosa (2020), when evaluating the simulation that was the object of this study, emphasized the importance of the teacher's role as a mediator to overcome deficiencies in the process of understanding the simulation and in the inferences made by students from it. Murtini *et al* (2024), when analyzing the use of natural selection simulation, concluded that guided inquiry education is efficient in promoting student learning based on personal experiences using PhET simulation means.

Final considerations

The use of virtual simulation allowed students to observe the process of natural selection occurring in successive generations and to manipulate factors that act upon it, which allowed them to draw their own conclusions about what they observed, thus promoting student protagonism. Factors involved in the simulation allowed students to make combinations with concepts of ecology and genetics, already present in their cognitive structure, which characterizes an indication of significant learning in most of the students analyzed. The simulation made the educational process playful and enjoyable, arousing the interest of students.

The use of information and communication technologies, in this case specifically the use of interactive virtual simulation on natural selection, proved to be an important strategy to assist the learning process and can be used in different teaching models, both in face-to-face teaching with teacher supervision in the computer room, and in hybrid or remote teaching, allowing students to manipulate the simulation guided by a script previously prepared by the teacher as a form of review activity or even as contextualization to start a discussion in the classroom, whether in person or virtually.

To future research, it is recommended to exploring Ausubel's theory in greater depth to assess knowledge retention over longer periods, especially when technological resources such as computer simulations are used. Meaningful and effective learning has the potential to remain in the cognitive memory for longer periods, compared to concepts assimilated through traditional methods.

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