Supporting the Learning of Evolution Theory Using an Educational Simulator

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This article analyzes Sim-Evolution, an educational simulator designed to help teachers presenting three basic principles of the theory of evolution by natural selection (TENS): the trait variation within a population, the heritability of trait variation, and the selective survival based on heritable traits. Sim-Evolution focuses on High School students, so its interface was designed to be joyful, helping to engage them. Although it was designed based on the concept of population genetics, knowing it is not a requirement for exploring TENS. Sim-Evolution models the population of a hypothetic bird species in two possible vegetations: forest or veld. Individuals of this bird species vary over two characteristics (color and beak type), with three possible phenotypes for each one. The user can choose individuals to form an initial population and monitor variation through successive generations. Birds breed independently of their phenotype, and natural selection (based on the fitness of each trait) was the only driven factor of population variation. Sim-Evolution was evaluated with High School students during a Biology class. Students were able to describe and analyze the simulation process from a scientific perspective, observing the phenomenon associated with TENS. They correctly associated the bird's evolution to different survivor rates associated with the different traits and identified evolution by natural selection as a population and not an individual/organism process. Our proposal opens the possibility that TENS simulator does not obligatorily require users to be familiar with population genetics concepts, which is especially interestingly for High School pedagogical uses.

Index Terms—**Learning Systems, Educational Simulator, Biology, Natural Selection, Genetics, Theory of Evolution.**

I. Introduction

Given the ubiquity of personal computers, smartphones, and other internet-connected devices, different aspects of school curricula and teaching-and-learning methods commonly made at school are being challenged [1], [2]. Recent studies [3]–[10] point out that the learning process using technological tools and computational resources can enhance the educational experience. The use of simulators as educational tools aim to increase students' engagement in classes and seems to help them to understand difficult concepts when they already have an abstract idea of the subject [11]–[16].

Computational resources can be used in natural science classes as an alternative for practical or experimental approaches when the time and space scales required by them are not compatible with the scholar environment. The ecology and evolution topics frequently pose these difficulties. If an educational simulator adequately models the underlying concepts of the biological phenomena under study, it may be used to support teaching, enabling students to explore the phenomena and understand it in a faster, more profound, and more pleasant way.

Through interactive simulators [17], students can gradually infer features about the phenomena. As the simulation unfolds, students explore the topic under study. Discoveries are made, predictions are confirmed or refuted by subsequent simulations, enhancing the comprehension of the phenomenon [1], [18]–[21]. It is important to notice that, when focusing on High School students, it is also essential to provide a joyful [22] and usable [14] environment that can empower the learning process.

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Under this vein, this article presents *Sim-Evolution*, an educational simulator to help teachers presenting the Charles Darwin's Theory of Evolution by Natural Selection (TENS). The use of *Sim-Evolution* along classes have the potential to ease students understanding about TENS and engage them in learning the topic. Although many students have been formally introduced to TENS, they might continue to present misconceptions on these topics [23]. Our intention with *Sim-Evolution* is to enable students to practice and comprehend it as a process that occurs at the population level (not as an event at the organism level, as usually and incorrect though by students [24]). Given that *Sim-Evolution* focuses on High School level, its interface was designed to be joyful, helping to engage students. Moreover, it is implemented for mobile devices to increase its access for students, given the lack of computers availability both in class and at students' homes.

Tibell and Harms [25] describes three basic biological principles that structure TENS: (i) variation, (ii) heredity and (iii) selection. We developed *Sim-Evolution* focusing on these principles, with an intention that a student that uses our simulator could observe aspects of trait variation within a population (variation principle), heritability of trait variation (heredity principle), and selective survival based on heritable traits (selection principle). Although our simulation design is based on Mendelian Genetics and population genetics, our intention was also that knowledge of these areas should not be a requisite for using *Sim-Evolution*.

Sim-Evolution mimics the scientific method process that enables students to explore TENS in an interactive approach. Using *Sim-Evolution*, students are invited to experiment with the simulator so they can observe laws of evolution and the genetic properties (genotypes) by analyzing species phenotypes and surviving populations. Such indirect analysis help students

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observe the three above concepts during classes. Therefore, this paper proposes to answer the following research question:

> *"Does Sim-Evolution enable students to observe evolution by natural selection as a population process and identify principles of variation, heredity, and selection by indirectly analyzing species' phenotypes?"*

The remaining of this article is structured as follows. Section II presents a brief background on evolution for better understanding the concepts modeled in *Sim-Evolution*. Section III presents related work. Section IV discusses *Sim-Evolution*'s design and implementation. Section V presents the experimental evaluation conducted with *Sim-Evolution*. Finally, Section VI concludes this article and discusses future work.

II. Evolution Background

Natural Selection (NS) is the essential mechanism of the Theory of Evolution (TE) presented by Darwin, in which a given environment contributes to the selection of the most suitable living beings to inhabit it. This proposition, which composes the TE of Species, postulates that the process of NS in each environment depends on three main aspects: variation in characteristics, differentiated reproduction, and heredity. In this context, only the individuals that have the ideal conditions for survival in a specific environment are successful in reproducing and transmitting to the next generations the same genetic and phenotype that guarantee the perpetuation of the species in that habitat. On the other hand, those with less favorable characteristics are not able to reproduce sufficiently and are slowly extinguished [26].

When Darwin divulged his TE, the genetic principles were not well defined, so his arguments did not count on a reliable explanation of how characteristics variability was originated and passed through generations [27]. Contemporary to Darwin, Mendel's work on hereditary transmission did not make a significant impact on that moment, being rediscovered only in the beginning of the 20th century. From studies of crosses of various species of plants, especially of peas, Mendel proposed that the existence of characteristics such as color, size, and shape is due to the presence of a pair of elementary units of heredity, which he named *factors* (now called *alleles of a gene*).

When reproducing, only one factor of each pair would be passed to the new organism created. Therefore, an organism could be homozygous for a gene (when presenting a pair of the same alleles) or heterozygous (when presenting a pair of different alleles for that specific gene), those being the possible genotypes. Also, in a heterozygous organism for a specific characteristic, the effects of some factors could overcome the others, being the first named the *dominant factor* and the latter the *recessive factor* [28].

The consolidation of Genetics in the first decades of the 20th century yielded significant contributions for evolutionary studies. Population genetics based on Mendelian's inheritance principles enabled the evolution process to be modeled and paved the way for the Modern Synthesis of Evolutionary Biology [27]. According to this theory, the evolution of an organism can be explained by mutations or recombination of its genetic material creating characteristics variability (or different phenotypes), followed by the process of natural selection. Thus, genetic characteristics that contribute to survival and reproduction become more common in a population, while detrimental phenotypes become rare. Such behavior is due to higher reproductive success rates among individuals with more advantageous characteristics. In this way, more individuals inherit these characteristics in the next generations.

Population genetics and evolution are basic topics in introductory Biology courses at the College level. However, at the High School level, is it not unusual that genetics and evolution are studied at different moments. Thus, educational approaches that enable the teaching and learning of TE without covering in details genetic concepts could be a useful tool for teachers.

III. Related Work

The use of games in educational contexts has been proposed as a strategy to strengthen the student's learning [29]. They are joyful applications that try stimulating students to learn through a role and playing context that includes a reward (such as points, challenges, goals achievements). Commonly the subject to be studied is part of the game-play. Generally, the major challenge for games in scientific scenarios is to achieve a compromise between the game-play/entertainment proprieties with the scientific modeling/experimentation process for usage at laboratory classes. One example in the TE subject is the video game Spore. It addresses evolution principles in a ludic and non-scientific manner [30]. Spore's commercial success is an indication of mainstream interest for content that targets at scientific evolutionary theories [31]. However, Spore was heavily criticized by educators for its unrealistic portrayal of evolution [30], [32]. The primary cause of criticism is Spore's focus on entertaining rather than education, not been based on evolution's major principles [32]. Thus, it was not designed to represent an accurate scientific view of evolution. Another main critic is that Spore presents evolution from an individual perspective in which organisms gain traits during their existence rather than present it as a population process driven by NS and survival differences related to biological variation. Spore is in the opposite direction of *Sim-Evolution*. *Sim-Evolution* is a ludic simulator that focuses on reproducing the concepts of the TENS.

On the other hand, simulators create a context of a desired scientific scenario. They are driven to provide a way to enable an experimental evaluation. They may represent a fertile field for the development of students' investigative abilities. They enable reflection, exploration, and formulation of hypotheses about a phenomenon, providing students with an understanding of macro events at a micro level [15], [21]. In the context of Biology, simulations developed for teaching and learning the concepts of natural selection have already been tested with success [21]. The Hamilton College project presents a simulator called *Evolve*. This simulator involves mendelian genetics, natural selection, genetic drift, and other concepts related to the evolution of a population of organisms, which can be

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configured in several ways, giving the students an investigative look at the concepts discussed [21]. However, focusing on graduate students, Evolve explores mainly statistical properties of population genetics. With a less friendly interface and more complex commands, Evolve was not designed for High School students, whereas *Sim-Evolution* is more appropriate for aiding the Biology learning process within these educational stages. Another difference is that Evolve is based on a population genetic approach and stimulates students to follow genotype variations within a population. In *Sim-Evolution*, on the other hand, since we intend to enable High School student to observe more basic principles of TENS (i.e., that it occurs by selection of variation within a population), we focused on phenotypic variation versus the genotypic presented at Evolve.

As can be observed, both games and simulators enable a try-and-error behavior. However, they differ in purpose. The try-and-error in games comes driven for the game context reward. In the simulator, the try-and-error arises from the intrinsic scientific method process, *i.e.*, repetitively running experiments by changing a set of parameters to comprehend the studied phenomenon through observed results. *Sim-Evolution* was conceived to provide such scientific experience.

IV. Sim-Evolution

Sim-Evolution was designed for being an educational simulator of TENS. It uses a scenario inspired by the records of the Galapagos finches observed by Darwin. *Sim-Evolution* models a population of a hypothetic bird species in two possible vegetations: forest or veld. Individuals of this bird species vary over two characteristics: color and beak type. Table I presents the possible phenotypes obtained from the two colors and three beak types.

TABLE I
The genotypes of the birds enables nine different phenotypes of plumage color and beak

Bird	Color	Beak	Genotype
A			AABB
B			AABb
C			AAbb
D			AaBB
E			AaBb
F			Aabb
G			aaBB
H			aaBb
I			aabb

As one may notice, from Table I, bird's characteristics are based on Mendel's law. Genes A and a determine the bird color, while genes B and b its beak type. Moreover, there are no dominant or recessive genes between A and a, and B and b. Thus, heterozygote birds are different from both the homozygote ones. Based on combinations of the bird genotypes, *Sim-Evolution* enables composing species with green, merged, and yellow plumages, and thin & pointed, short, and curved beak types.

A. *Sim-Evolution Interface*

Sim-Evolution starts by asking the user to select the desired simulation mode: *default* or *custom*. The former leads an environment selection screen with two possible options: *forest* or *veld*. Once the environment is chosen, the user can select the initial population of bird species for the simulation, by choosing four out of the nine possible bird phenotypes, as can be seen in Fig. 1.

Fig. 1. Population setup: can start with up to four birds' phenotype

The simulation screen presents the environment chosen and the bird phenotypes present in the simulation population, together with their quantities, as seen in Fig. 2. As the simulation unfolds, bird quantities are updated according to their breeding and predating.

(a) forest scenario

(b) veld scenario

Fig. 2. NS occurring on birds' populations in both environments

At any moment during the simulation, the user can see the bird's population growth (or decrease) on a timeline (Fig. 3). The chart presents the bird phenotypes and their respective quantities throughout the simulation. Thus, it enables the user to check the results of the NS process, for a given initial population.

The *custom* simulation type enables the user to provide the phenotypes fitness values (feeding and predating rates). Thus,

Fig. 3. Bird survival chart: bird's phenotypes and population

defining the birds' chance of survival and reproduction. Fig. 4 presents the custom settings screen. The selective survival values in the simulation is discussed in detail in Section IV-C.

Fig. 4. Phenotypes settings: fitness rates for feeding and predating

B. Simulation Design

As mentioned in Section I, *Sim-Evolution* focuses on three key principles of the evolution theory: (i) trait variation within a population, (ii) heritability of trait variation, and (iii) selective survival based on heritable traits.

For a clear comprehension of the evolutionary process, NS was the only driven factor of evolution acting in the bird population of the simulator. For other aspects, the population resemble a Hardy-Weinberg model: (i) it does not include the occurrence of mutations; (ii) it does not include migrations; (iii) breeding occurs randomly between any two birds [21].

Sim-Evolution enables birds to breed independently of their phenotype. Through genotype combination in a Cartesian fashion using the *Punnet* method descendants are generated. As seen in Table I, different phenotypes are given by the different combination of genes A, a, B and b. Thus, trait variation is achieved during the simulation. We expect that students shall observe this characteristic by the rise of different phenotypes as the simulation unfolds.

Each different simulation environment (forest, veld or custom) defines different predating rates based on the plumage color and feeding rates based on the beak type. The forest and veld environments have predefined values, while in the custom simulation, those values are user-defined. The forest scenario is characterized by high tree density and predominantly green color, as seen in Fig. 2a. Thus, birds with green plumage are better camouflaged in the forest scenario and are more likely to survive in this environment, having lower predating rates. As for beak types, birds with curved beaks are better fed in the forest where there is a more significant supply of fruits and seeds.

On the other hand, the veld environment is a scenario typified by the predominance of grass plants and yellowish coloration due to the dry climate, as seen in Fig. 2b. Thus, birds with yellowish plumage have an advantage in camouflaging, thus having lower predating rates. As for beak types, birds with thin & pointed beak are better fed in the veld where they would feed mainly on insects and larvae. We expect that these different fitness values for each different environment shall enable students to relate the birds' phenotype to its selective survival on the chosen environment.

The idea behind different feeding rates is that birds whose beak phenotype have a high fitness are more likely to feed and therefore have more energy. Birds breeding may generate a random number of descendants, which is related to their feeding rates. Thus, birds feeding level is associated with their ability to reproduce more, which increase their chances to perpetuate their lineage and allowing the simulation to tackle the heritability of trait variation concept. That approach mimics the real world by both generating number of descendants and considering that well-fed parents are more likely to generate more descendants. We expect that students shall observe this characteristic by the increase of populations whose phenotype are more able to feed in the environment in detriment to others.

C. Simulation Algorithm

The simulation process uses two main variables: predating rates and feeding rates. Each environment e (*default* or *custom*) defines predating rates for the three different plumage colors and the feeding rates for the three beak shapes.

Algorithm 1 describes the simulation process. It receives as input the environment e and the set of birds S representing the initial population chosen by the user (see Fig. 1). The algorithm executes a loop cycle of feeding, breeding, predating, and life span degradation. The simulation runs until no more birds exist in the environment or the simulation reaches a duration threshold (τ).

Algorithm 1 Simulation(e, S)

1: $t \leftarrow 1$
2: **while** $(|S| > 0) \wedge (t < \tau)$ **do**
3: $\quad S \leftarrow Feeding(S, e)$
4: $\quad S \leftarrow S \cup Breeding(S, e)$
5: $\quad S \leftarrow Predating(S, e)$
6: $\quad S \leftarrow LifeSpan(S)$
7: $\quad t \leftarrow t + 1$
8: **end while**

The birds' feeding function ($Feeding(S, e)$ - line 3) increases the energy levels of all birds $s \in S$ according to their beak shape fitness for environment e. Additionally, the birds' breeding function ($Breeding(S, e)$ - line 4) randomly selects two birds $s_1, s_2 \in S$ and combine their genotypes to generate their descendants. Genotype combination in function *Breeding* is performed in a Cartesian fashion using the *Punnet* method for birds s_1 and s_2. The number of descendants generated is also related to their beak shape fitness.

Table II relates the feeding rate with the beak shape fitness. Such a level of fitness limits the chances for both increasing energy in function *Feeding* and for the number of descendants

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in function $Breeding$. The idea behind that table is that birds whose beak phenotype have a high fitness are more likely to feed and therefore have more energy in the context of breeding.

TABLE II
ASSOCIATION BETWEEN THE BEAK SHAPE FITNESS FOR ENVIRONMENT AND THE CHANCES FOR INCREASING THE ENERGY OF BIRDS DURING FEEDING AND FOR ESTABLISHING THEIR NUMBER OF DESCENDANTS DURING BREEDING

Feeding rate	**Beak shape fitness**	**Max. energy increase value**	**Max. descendants**
0.01 - 0.15	low	2	2
0.16 - 0.30	medium	3	4
0.31 - 1.00	high	5	6

The Birds' predating function ($Predating(S, e)$ - line 5) follows NS principles. The chance of a bird to be predated is related to its plumage color fitness for the environment e. Table III establishes the correspondence of the predating rate of a bird with its plumage color fitness. The idea behind Table III is that the higher the plumage fitness, the higher are the chances of survival. The user in the *custom* mode may define them in a human in the loop basis (see Fig. 4).

TABLE III
CHANCE OF BEING PREDATED ACCORDING TO PLUMAGE COLOR FITNESS FOR THE ENVIRONMENT

Predating rate	**Plumage color fitness**	**Chance of being predated**
0.01 - 0.15	high	low
0.16 - 0.30	medium	medium
0.31 - 1.00	low	high

Finally, function $LifeSpan$ decreases the energy of every bird in S, representing the natural loss of energy by birds due to its life process. Birds whose energy value is equal to zero are removed from S.

V. EXPERIMENTAL EVALUATION

The experimental evaluation consisted in letting students run *Sim-Evolution* and check if it allowed them to observe TENS concepts as a result of their trial-and-error executions. The Simulator was developed for Android and is available at Google Play Store[1]. This enables its usage both at the classroom and at home. Additionally, the application source code, evaluation form, and experimental results are also available[2]. The evaluation was divided into both quantitative and qualitative evaluation. It was conducted with 45 students at High School during a Biology class. For the experiment conduction, a script was produced containing basic instructions about the simulator.

Students initially filled the characterization part of the evaluation form, that include questions about age, grade, and background knowledge on the subject: TE, NS, MG, Principles of Classical Genetics (PCG), and Probabilities in Genetics (PB). The age of students varied between 14 and 17 with an average of 15. They were from the first year of High School. Figure 5 presents their prior knowledge on the above subjects. Although they have been introduced on these subjects, some of them did not answer that they knew PCG and PB.

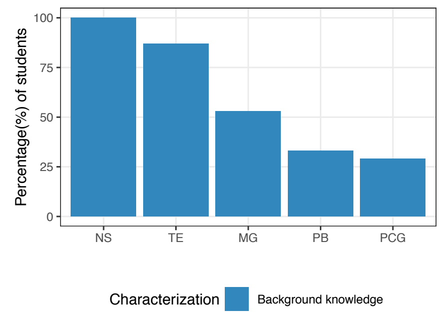

Fig. 5. Prior student knowledge

Then, they were divided into groups of 5 to 6 members (due to limitations on mobile devices available during class) and left them to use *Sim-Evolution* freely. After finishing the simulations, each student separately filled the remainder of the evaluation form (composed of 18 questions). The first four questions ($Q1$-$Q4$) were designed to measure students' observations about the simulated environment. They evaluated the students' perception about how adapted a phenotype is to a given environment, besides the relation of birds' characteristics to natural processes.

$Q1$ asked, "After simulating the forest environment, would you say that birds with which of the following characteristics were favored?". $Q2$ asked, "After simulating the veld environment, would you say that birds with which of the following characteristics were favored?" Possible answers for $Q1$ and $Q2$ were: none, plumage color (green, merged, yellow), and beak shape (curved, short, thin&pointed). For these questions, students could mark more than one possible answer. $Q3$ asked, "The birds' beak shape was related to the probability of?", and $Q4$ asked, "The birds' plumage color was related to the probability of?" Possible answers for $Q3$ and $Q4$ were: none, feeding, breeding, and predating.

As discussed in Section IV-B, the forest and veld environments are programmed to favor different phenotypes. Moreover, beak shape and plumage color impact in different natural processes. The assumption here is that student responses matching this programming would indicate *Sim-Evolution*'s potential for educational support. Figures 6 and 7 summarize the results for questions ($Q1$-$Q4$).

Results for $Q1$ and $Q2$ (Figure 6) indicate that students perceived NS was more observable through the plumage color than beak shape. Also, results for $Q3$ and $Q4$ (Figure 7) indicate that most of the students correctly observed the relationship between the beak type to feeding and the plumage color to predating. However, students could not observe the relationship between the beak type and breeding.

An explanation for the results regarding Questions $Q1$ to $Q4$ is related to the fact that students have perceived more the predating than the feeding and breeding process. For example, a green bird with a thin & pointed beak would tend to withstand longer in the forest than a yellow bird with a

[1]https://play.google.com/store/apps/developer?id=GPCA
[2]http://eic.cefet-rj.br/~eogasawara/sim-evolution

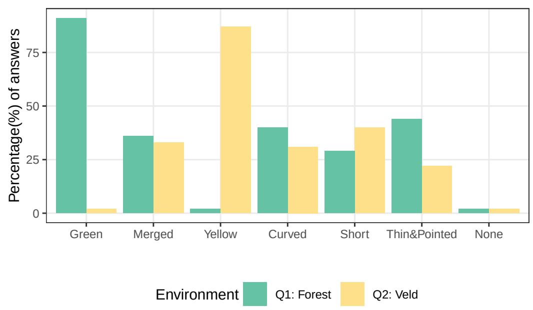

Fig. 6. Perception of plumage color and beak shape phenotypes

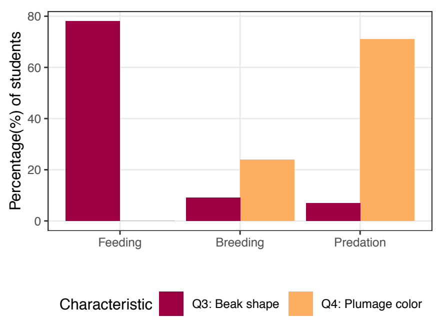

Fig. 7. Perception of phenotype on feeding, breeding, and predating

curved beak, although the curved beak gives the bird greater chances of feeding. These results open the possibility for the teacher to reinforce the concept of fitness in the classroom: the phenotypic trait of the individuals present different *adaptive values* for an environment.

Questions $Q5$-$Q8$ targeted a qualitative evaluation, each one composed of a sentence that should be evaluated using a Likert scale from 1 (totally disagree) to 4 (totally agree). Students also had to justify their answer based on some experience or situation he or she encountered when using *Sim-Evolution*. These set of questions tests the hypotheses that one could observe evolution occurring as population process and the three principles of TENS (ie. variation, heredity and selection). The hypotheses are described as follows:

H1 The student observes that evolution does not inhibit variation within a population ($Q5$).
H2 The student observes the evolutionary process occurs at a population level, and not at the individual level (i.e., of a single organism) ($Q6$).
H3 The student observes that evolution is a process that did not occur by passing traits through generations that were acquired by use or disuse during a lifetime (*i.e.*, inheritance of acquired characteristics) ($Q7$).
H4 The student observes that biological adaptation is related to the survival of organisms more adaptable to a given environment, in the process of evolution (*i.e.*, natural selection) ($Q8$).

Fig. 8 presents the evaluation for each hypothesis according to the degree of correctness achieved by students. Question $Q5$ addressed the first hypothesis by sentencing "With the natural selection process, there is no variation of characteristics in the population: only the adapted form survives" (variation principle). The expected response for $Q5$ is disagree. It is purposely wrong, to evaluate whether *Sim-Evolution* enables us to problematize the mistaken notion that a population can be formed by individuals perfectly adapted to their environment. Seventeen students disagreed with $Q5$. Although the results seem not appropriate, they may be attributed to a common-sense preconception that the result of the evolutionary process is a "species ideally form" perfectly adapted to a specific environment. But even students that incorrectly agreed with the sentence could perceive that variations in the population still occurred. This explanation is supported by the following justification provided by a student that agreed with $Q5$.

> "At the end of the simulation birds of the same species survived but they had variations, **was not just one that survived**". [emphasis added]

Question $Q6$ addressed the second hypothesis by sentencing "The biological evolution by natural selection is a process that occurs in a population, not being possible to observe it following only the life of an organism individually". The expected response is agreeing. It is correct and is a crucial point for evolution teaching. Most students (36) correctly agreed with $Q6$, identifying that it is not possible to observe the natural selection process over an individual. The following justification supports this explanation:

> "The entire context should be observed which includes the initial number of organisms observed, number of predators and different types of them, habitat, feeding options. Even because observing a single organism cannot be noticed any difference since for some change it is necessary to observe several 'generations'."

Question $Q7$ addressed the third hypotheses by sentencing "To best suit an environment, a bird can change its color or the shape of its beak. This process is called biological adaptation". The expected response is disagreeing. It is purposely wrong. Only sixteen students disagreed with statement $Q7$. Our intention was to evaluate the students' understanding that evolution is not based on the inheritance of acquired traits, but in the herdability of traits that organisms already have (heredity principle). This result indicates that Lamarckian evolution is a very strong idea in students. Even so, some students indicate that in addition to realizing that the birds generated were the result of a genetic combination of their parents, most understood that the following generations are the product of a set of combinatorial possibilities and random selection, exempt of an intentional element. This kind of answer should indicate that *Sim-Evolution* could provide ways of discussing these misconceptions within the classroom. The following justification supports this explanation:

> "The bird cannot change its genetic characteristics. By having features not compatible with the habitat, the species was predated."

Question $Q8$ addressed the fourth hypotheses by sentencing "Biological adaptation is perceived when, over successive generations, we observe the survival of organisms that present the characteristics most appropriate to a given situation" (selection principle). The expected response is agreeing. The results were like Question $Q6$. Most of the students (43) agreed with it, which means that they associated evolution as different

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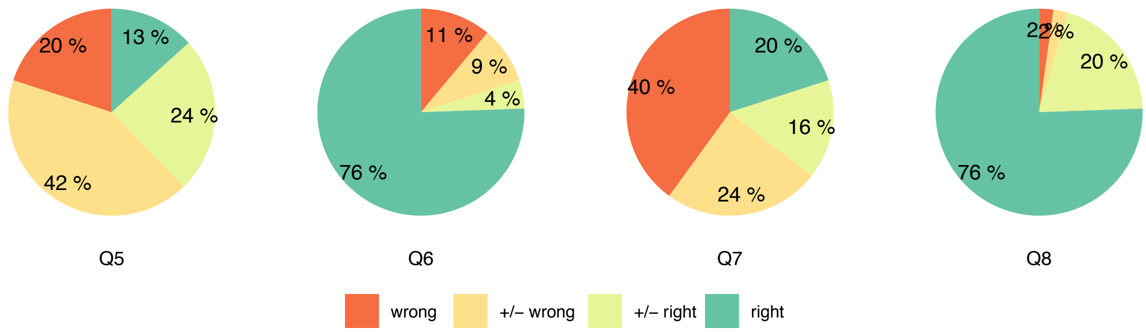

Fig. 8. Evaluation of hypotheses $H1$ ($Q5$), $H2$ ($Q6$), $H3$ ($Q7$), and $H4$ ($Q8$) according to the degree of correctness achieved by students

survivor rates between organisms that possess different traits. Thus, we consider that *Sim-Evolution* was able to address the concept of NS in a population as identified by the students. The following justification supports this impression:

> "At the end of the simulation, only those that had characteristics to survive in that environment survived."

Questions $Q9$ to $Q14$ evaluated if students agreed with sentences about features of *Sim-Evolution*. Question $Q9$ sentenced that "*Sim-Evolution* aids the understanding of the concepts of TE" (comprehension). Question $Q10$ sentenced that "descriptions and help support of *Sim-Evolution* aids its usage" (help system). Question $Q11$ sentenced "the graphical presentation aid in understanding the simulation (visualization)". Question $Q12$ sentenced "statistics presented by simulator aids in the analysis of bird survival" (statistics). Question $Q13$ sentenced "phenotypes configuration features enriches the simulation" (phenotypes setup). Question $Q14$ sentenced "the custom setup enables a better comprehension of the modeled phenomenon" (simulation setup). Figure 9 presents the percentage of students that agreed with sentences $Q9$ to $Q14$. In all questions, the features of *Sim-Evolution* have been accepted by more than half of students. Sentence $Q9$ was accepted by almost all students. It is an important result, since it was one of the main goals of the simulator. Nevertheless, the visualization feature was the worst ranked one presented at *Sim-Evolution*, indicating that the data display should be improved. Some students indicated that simulation events were displayed too fast.

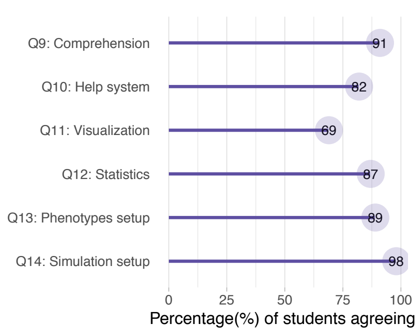

Fig. 9. Evaluation of simulator features

Finally, questions $Q15$ to $Q18$ targeted the usability of *Sim-Evolution*. Question $Q15$ asked, "Is *Sim-Evolution* ease to use?". Question $Q16$ asked, "Does *Sim-Evolution* need background theory for using it?". $Q17$ asked, "Are *Sim-Evolution* features coherent with each other?". $Q18$ asked, "Does *Sim-Evolution* require prior computational skills before using?". Answers are depicted in Figure 10. Almost all students agreed with $Q15$, finding *Sim-Evolution* ease to use. Approximately half of the students agreed that background on TE is a need for understanding the Simulator. This is an interesting result, since *Sim-Evolution* was conceived to aid students that already knew TE background. Almost all students agreed with $Q17$ and disagreed with $Q18$. These are expected results, since the simulator was designed to straightforward in its usage and to not require any additional skill than the ones presented in other mobile applications.

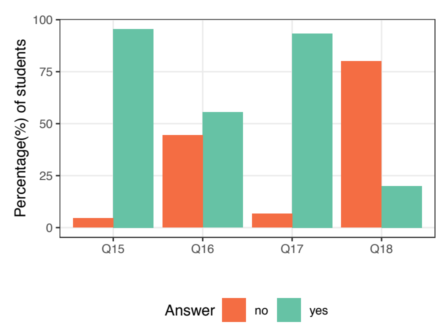

Fig. 10. Evaluation of usability

VI. Conclusion

The results of our experimental evaluation suggest that *Sim-Evolution* can be an important auxiliary tool for helping teachers to explore TENS. By running it, one could perceive TENS as a population process, not as an individual organism change through time. This is a significant difference in our approach when compared with others like Spore [30]. This was achieved due to three basic biological principles that structure TENS in *Sim-Evolution*: (i) variation, (ii) heredity, and (iii) selection, which enable students to perceive those different individual traits were associated with different fitness.

Specifically, the design proposed for *Sim-Evolution* is novel as it explores the subject of TENS through the indirect analysis of phenotypic variations through generations. Such an approach is interesting as it mimics real-work scientific

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investigation, where scientists commonly study a phenomenon from indirect analysis of available data. Specifically, in our context, our proposal opens the possibility that TENS simulator does not mandatorily require users to be familiarly with population genetics concepts (as it occurs in Evolve [21]), which is especially interestingly for High School usage.

From the experimental evaluation, students were able to describe and analyze the simulation process in *Sim-Evolution* from the scientific point of view, observing the phenomenon associated with TENS. It enables the reinforcement of cognitive skills associated with a scientific understanding of the TENS that might not be achieved without such type of practice. The cognitive mobilization of the students provoked by the open questions of the conceptual evaluation in the face of their experience with the *Sim-Evolution* denotes that it can be an active component in teaching-and-learning environment.

We notice, however, some issues related by students during their experimental evaluation. They did not impact the overall assessment results but pointed out the need to refine the simulator. The programming of music events and message display should be reviewed and corrected in a future version of the simulator. We also note that the simulator generated inconsistent behavior when used on *Android APIs* versions that were different from the ones used during game development.

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