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Not by Design Alone! Modelling Practices to Identify Students' Frameworks of Evolution in Real-Life Contexts

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Despite being a fundamental concept in biology, evolution continues to be one of the most challenging topics to teach in science education. Ideas of evolution emphasising anatomical or behavioural features of individuals, as opposed to the interplay between genetics and the environment, are reinforced through language and culture, making them robust and persistent in the student population at all educational levels. Model-based reasoning has been reported to be useful for students to make sense of process-based science content, combining epistemological with linguistic and value dimensions. However, there is a dearth of evidence in biology education showing how modelling can instigate epistemological maturity, specifically about issues of agency and design in evolution by natural selection. Drawing on this perspective, this study focuses on describing the nature of students' ideas while modelling the resistance developed by a population of mosquitoes in a lagoon after an insecticide is introduced. Data collection includes students' written reports and drawings, which were analysed with content and discourse analysis. The findings show that, at first, students believed adaptation to feature at will was a behavioural characteristic instigated by a pre-existing design. After modelling the process of natural selection, the explanations appeared to improve (from Lamarckian to Neo-Darwinian views), and most groups showed accurate explanations about adaptation.

Keywords: modelling, evolution, adaptation, natural selection, evolution frameworks

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Ne samo po zasnovi – prakse modeliranja za prepoznavanje učenčevega razumevanja evolucije v okviru resničnega življenja

Noa Ageitos, Laura Colucci-Gray in Blanca Puig

Čeprav je evolucija temeljni koncept v biologiji, je še vedno ena najzahtevnejših tematik pri poučevanju v naravoslovnem izobraževanju. Ideje o evoluciji, osredinjene na anatomske ali vedenjske prvine osebka, so v primerjavi z vzajemnim učinkovanjem genetike in okolja, okrepljene prek jezika in kulture, kar jih napravlja robustne in vztrajnostne med učenci na vseh stopnjah izobraževanja. Na modelu koncipirano razmišljanje naj bi bilo uporabno za učence, da osmislijo procesno temelječe znanstvene vsebine, ki združujejo epistemološke razsežnosti z jezikovnimi in vrednostnimi. V biološkem izobraževanju pa se kaže primanjkljaj tistih raziskav, ki bi prikazale, kako lahko modeliranje spodbudi epistemološko zrelost, zlasti glede vprašanj delovanja in oblikovanja v evoluciji z naravno selekcijo. Na podlagi te perspektive se ta študija osredinja na opisovanje narave idej učencev, medtem ko modelira odpornost, ki jo razvije populacija komarjev v laguni po uvedbi insekticida. Zbrani podatki obsegajo pisna poročila učencev in risbe, za katere je bila storjena vsebinska in diskurzivna analiza. Ugotovitve kažejo, da so učenci sprva verjeli, da je prilagoditev na poljubno lastnost vedenjska značilnost, ki jo je sprožila obstoječa zasnova. Po modeliranju procesa naravne selekcije se zdi, da so se razlage izboljšale (od Lamarckovih do neodarvinističnih pogledov), pri čemer je večina skupin ponudila natančne razlage o prilagajanju.

Ključne besede: modeliranje, evolucija, prilagoditev, naravna selekcija, evolucijski okviri

Introduction

A large body of research on evolution in biology education exists, since evolution is a central concept in biology and one of the most challenging to learn as well as to teach (Andrews et al., 2017). Students often hold alternative conceptions about the main mechanisms of evolutionary changes and what the theory of evolution explains (Siani & Yarden, 2021). Typically, natural selection is framed as a direct and causal process (Ferrari & Chi, 1998), which might be related to intentional, instrumental, or teleological thinking. For instance, when explaining the evolution of pesticide resistance in a population of insects, students may explain the phenomenon in terms of linear causality, suggesting that the occurrence of a mutation resulted in resistance (Cooper, 2016). With the goal of understanding how to improve students' ideas on evolution, diverse instructional models have been proposed; modelling-based instruction has proved to be useful in identifying students' ideas and promoting reasoning about evolution. In line with d'Apollonia et al. (2004), this study focuses on students' development of models and/or explanatory frameworks to organise knowledge and to make explanations and predictions about natural phenomena related to the process of natural selection. It is through the iterative nature of model-based reasoning that students build knowledge about the phenomenon under study but, most importantly, so that they can think and reason with their own ideas (Passmore et al., 2014). Vattam et al. (2011) view student-constructed models as tools for facilitating students' thinking about the causal and mechanistic relationships that are inherent in biological systems. In a similar vein, this research adopted the notion of modelling as a process that may not only reveal students' reasoning but may also enable the construction of thinking frameworks on evolutionary theory, supporting epistemic maturity about the key questions of linear causality and agency in evolutionary processes. We suggest that this is an important role of biology education to prepare students to understand and grapple with future thinking about change, survival, and variability on a planet in flux (Colucci-Gray & Gray, 2022).

Building on current research on alternative frameworks, this paper advances understanding of the value of modelling in surfacing the fluidity of such frameworks vis-à-vis the ongoing debates and dynamic thinking in evolutionary theory seeking to grapple with environmental change.

Focus of the study

Despite extensive research in evolutionary biology focussing on adaptive and selective explanations for evolutionary change, less is known about the processes supporting students' reasoning while seeking to explain the same phenomena. This study is part of this line of research (Beggrow & Nehm 2012), and it assumes that modelling, as a process of embodied thinking through doing, can play a central role in evolution learning. We consider modelling, both as a scientific and educational practice, that combines conceptual and practical dimensions of thinking and doing (Nathan, 2022); the making of a model engages 'the how' as well as 'the why' of a process and is proposed here as being particularly helpful in engaging with thinking about evolutionary processes, as they occur through a variety of linear and non-linear mechanisms (Colucci-Gray & Gray, 2022). Specifically, we look at the ways in which modelling through drawing can support students' articulation of the role of natural selection and how this process can support epistemological maturity on issues of agency and design within a systemic perspective. The research questions are:

1) In what way and to what extent do students' models of evolution differ?
2) What evolution frameworks underpin students' explanations when building and evaluating a model of evolution? And how do these frameworks change?

Background

Key debates in evolutionary thinking in biology

A lively debate characterises evolutionary biology both on the question of agency and of inheritance, that is, the process through which so-called 'adaptive traits' are 'passed on' to the next generation. In these debates, the process of linear causality as the main mechanism for explanation is discussed according to two main alternative positions.

One idea rests on genetic programming, which is quite pre-formationist; while gaining traction in some research fields, such as genetic engineering, it remains a contested idea in evolutionary biology and genetics of populations. For example, simple random changes in the proportion of genes, caused by the fact that different families have different numbers of offspring, may account for differential patterns of inheritance; equally, genetic drift may play some evolutionary role in small populations.

However, if we exclude this approach, the other route to explaining evolutionary change rests on the notion of 'developmental dualism' whereby some features might develop under the aegis of the genes (Konner, 2022), while others are shaped by the environment. This second aspect points to a dual developmental process that reflects the old and tangled nature-nurture dilemma, leading to ongoing difficulties in synthesising knowledge of genetic development with an understanding of evolutionary processes (Beggrow & Nehm, 2012; Oyama, 2000;).

In *Evolution in Four Dimensions,* Eva Jablonka and Marion J. Lamb (2005) point to new knowledge on genes and genomes and challenge dualist assumptions. They argue that the concept of inheritance currently used in evolutionary thinking is far too narrow and must be widened to integrate results from molecular biology as well as behavioural sciences. This approach to evolution calls for a systemic view, whereby the development of individual organisms is part of a set of nested systems and their changes over time.

Despite the ongoing debates, evolution instruction often focuses on more simplistic approaches, presented as mutually exclusive, as a succession of linear explanations provided by singular scientists over time (Brigandt, 2020). Considering this gap, this paper focuses on the characteristic of biological thinking, which is to offer a multiplicity of theories and frameworks *with which to think*.

Alternative frameworks about evolution commonly used in the classroom

Three alternative and distinct frameworks of evolution are common and commonly found when addressing the topic of evolution in the classroom.

The first one, the Darwinist framework, is presented as the most up-to-date and accepted theory, which is centred upon the concept of natural selection. However, as reported by Depew (2020), while Charles Darwin emphasised the correspondence between organisms and the environment that results from natural selection and adaptation (e.g., in the formation of specific ecological niches), he was never concerned with the interpretive power of language. In this view, natural selection is often understood to be akin to a mechanism of cause and effect, of the likes of Newtonian physics, as a force shaping a passive organism.

These assumptions about agency and passivity, linearity, and interactivity make understanding of selection problematic in two important ways. Firstly, Nature is discursively positioned as being *outside* the organisms and acting upon them. This view translates the concept of natural selection as an external force discriminating the fit from the unfit; but it is also at the root of a second, common conception, which is often associated with Lamarckian ideas.

To this regard, a second frame of Neo-Darwinist ideas has gathered force around the notion of a selfish gene, according to which any action is a supremely self-serving one on the part of the actor, devoid of motivation to serve the larger group to which the actor belongs. The Neo-Darwinist framework has gained traction in popular culture, and it is frequently introduced in Biology instruction, for instance, in Spanish textbooks in higher education, even though it is not the most recent interpretation in biological thinking. Consensus among the scientific community exists regarding the epigenetic contributions to evolutionary theory, as reported by Jablonka and Lamb (2005), yet these ideas have not acquired visibility in school teaching.

This points to a third frame, suggesting that the inheritance of developmentally acquired variation and the transmission of induced or accidental epigenetic modification might be adaptive. As opposed to seeing evolution as the display of properties residing either in the individual or in the environment, evolutionary features of organisms may thus be more powerfully seen as produced and emergent in interaction (Oyama, 2000).

With the goal of understanding students' frameworks on evolution, we look at models as epistemic and dynamic tools that may be useful to support the elaboration of different explanations and predictions for creating new knowledge and to generate potentially new frameworks (Gouvea & Passmore, 2017).

Modelling practices in learning and teaching about evolution

Several approaches to models and modelling exist in science education. In this study, models are considered to be abstractions or simplified representations of a phenomenon used to create explanations and/or predictions (Gericke et al., 2013). Scientific models have different functions (Mendonça & Justi, 2013), such as to simplify complex phenomena in order to identify key variables and dimensions (Gilbert, 2008), support explanations of natural phenomena and construct theories (Passmore & Stewart, 2002), make predictions (Clement, 2008) and provide the basis for experimental proposals and interpretations (Morrison & Morgan, 1999); communicate scientific knowledge (Nersessian, 1999), or assist in the visualisation of abstract entities (Gilbert, 2008). Sometimes, more than one model is used because no single model can capture all the relevant features; or, more interestingly, the possibility to *think with* different models can generate different insights into the problem under study, especially when studying complex phenomena, such as global climate change, involving a multiplicity of interacting factors (Lloyd, 2015). Hence, models are not intended to describe or represent the natural world with perfect fidelity but to offer a version much like it, though less complicated and amenable to change (Gilbert, 2008).

Parke and Plutinski (2022) remind us that it is common in biology to use the terms 'theory' and 'model' almost interchangeably as a key aspect of how biologists go about producing their theories and explanations is literally by building and manipulating their own models. The thinking and the making are intertwined, in the same way models and theories become almost interchangeable (Nathan, 2020). Moreover, biological models, more than any other domain, capture a wide range of metaphorical expressions, a rich imagery that becomes associated with concrete phenomena, and are culturally transferred in everyday language (Brigandt, 2020). Such models may be rendered as physical artefacts but also as diagrammatic representations, a visual grammar, in which arrows may always be used to associate signifiers with signified, within a rich ecology of signs, a multiplicity of nested logics, which are recursively pursued and identified. In this study, we focus on models as external representations, considered as dynamic forms of knowing (Pérez Echevarría & Scheuer, 2009) connected to mental processes and amenable to being communicated and manipulated over the course of instruction.

Method

Context

This study adopts a qualitative case-study approach and draws upon discourse analysis as a method for analysing the discursive and rhetorical functions of modelling, understood as a repertoire of students' biological thinking (Ageitos et al., 2019; Brigandt, 2020). The study runs as a longitudinal project over two school years (2014–2016), focussing on learning genetics and evolution through modelling and argumentation practices.

The project took place in a state high school located in Galicia (Northwest of Spain). The participants were 16–17-year-old students (N=20) and their biology teachers. The school was set in a semi-rural location with a medium level of socio-economic advantage. The students (7 male, 13 female) had chosen a scientific itinerary and had previously participated in modelling and argumentation tasks.

The students worked in groups (n=5) over the entire course of the project, with minor changes between the first and second year due to new students enrolling in and dis-enrolling from the school. The teacher had more than 15 years of experience and had previously participated in research on modelling. While engaging in this project, he participated in two workshops with the researchers on argumentation and modelling. His role consisted of guiding the lessons and supporting students to participate in the tasks, providing help when needed.

The design of the activities was led by the authors and negotiated with the teacher. In the first year, the project consisted of four tasks: 1) students modelling gene expression, 2) application of the model to a different context, 3) students' engagement in argumentation about genetic testing, and 4) students' application of their knowledge of evolution to explain the evolutionary relationship between sickle cell disease and malaria. The analysis of the first-year tasks revealed difficulties and misconceptions about genetics and evolution (Authors, 2019); thus, in the second year, the design was modified to help students overcome them.

The second-year project consisted of three tasks. The first focused on the metaknowledge of modelling. The second required students to apply the model of gene expression to explain the development of an animal disease with a genetic component triggered by stress, as it has been suggested that specific emphasis on genetics during instruction may enhance conceptual change in evolution (Kampourakis & Zogza, 2009). The last activity, *Can a mosquito population change when insecticide appears in a lagoon?*, involved students in argumentation as well as modelling, which is the focus of this study.

Description of the task

The task analysed corresponds to the last activity of the project. It contained three phases: 1) using knowledge about evolution to assess a case, 2) simulating natural selection and building a model about evolution, and 3) evaluating the model considering Lamarck and Darwin's theories of evolution. This structure was derived from considering that modelling-based activities involve the construction, communication, and evaluation of knowledge (Schwartz, 2009); therefore, in this case, the focus was the explanation of an evolutionary phenomenon.

Phase 1: the case of DDT (insecticide) to eradicate mosquitoes causing malaria in a lagoon was presented to students. While the case was presented as historical and hypothetical, students were informed of current research showing that, with climate change, malaria is, in fact, a recurring problem in particular regions of the world (Sainz-Elipe et al., 2010) and even extending to new regions where it had been previously eradicated. The case was presented as follows: 'A farmer on the east coast grows rice in a lagoon and wants to use an insecticide to protect his crops. However, his neighbour is concerned that the use of DDT may create a resistant population of mosquitoes, and, therefore, increase the cases of malaria'. This ecosystem corresponds to a Mediterranean area in which malaria was present. Students were asked to reason in small groups (N=5) about the possibility of mosquitoes developing resistance against the insecticide and decide with whom they would agree more and justify it.

This initial phase was designed to elicit students' prior knowledge and understanding of evolutionary processes and the elaboration of explanations according to their own personal frameworks (Gilbert, 2008).

Phase 2: The above situation was later simulated by students using pieces of foam representing the mosquitoes (brown ones (the non-resistant mosquitoes) and black ones (the resistant) ones). A few mosquitoes were added to the area, and in each generation, each mosquito created another mosquito. When the insecticide appeared, each resistant mosquito created another mosquito, and the non-resistant mosquitoes disappeared. This simulation was repeated twice, once with and once without insecticide in the environment. The results were represented in graphs. Each group explained what happened in each situation and the differences between the two simulations. Afterwards, they were asked to build a model explaining how evolution was affecting the different responses in each context. Students were not provided with instructions on how to build the model, they were invited to use any material they wanted, and they were invited to then report their model in writing by creating a representation. This second phase was designed to provide students with tools for thinking in action, each time introducing new variables and modifying their connections to craft new structural knowledge (Mayer, 2015). The analysis considered such representations alongside students' evaluations (Phase 3) to explore the discursive shifts from a singularity to a multiplicity of pathways and from linear to systemic configurations.

Phase 3: Students evaluated their models by referring to Darwinian, Lamarckian, and Neo-Darwinian theories and offered evidence and justification for which model they felt most closely aligned. This phase was designed to elicit awareness of students' own thinking, specifically in relation to the nature of causality and agency of natural selection (Vattam, 2011), and to reflect on the role of Nature and the environment as external or as part of the evolutionary destiny of the organisms, thus integrating ideas from a range of disciplinary perspectives in biology (Oyama, 2000).

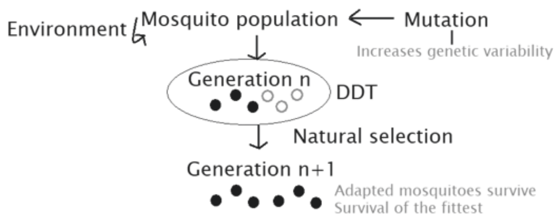
Data collection and analysis

All sessions were attended by Authors 1 and 3, who took field notes and collected the models and written reports elaborated by the five groups.

For the examination of both research questions, a reference model of evolution was elaborated by the authors from the two most alternative frameworks presented in Spanish classrooms (i.e., Neo-Darwinian and Lamarckian), which provided a dialectics between the idea of direct transmission from parental adaptations (Lamarck) and that of adaptation because of selection operated through the organisms' interactions within a particular environment (Darwin) as well as variability in the genetic pool (Neo-Darwinism).

Figure 1

Neo-Darwinian reference model.

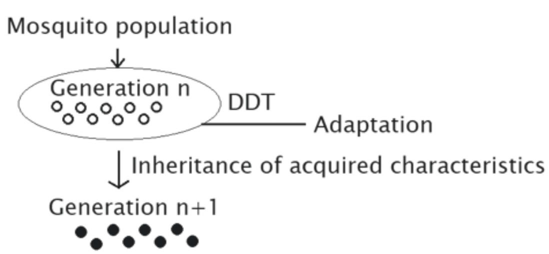


In the model above (Figure 1), a population of mosquitoes with genetic variation is represented throughout several generations. It encounters an insecticide (DDT) in the environment, which leads to the natural selection of the fittest individuals (the ones who are resistant to the insecticide), resulting in a resistant population against the insecticide and surviving. The survival of the individuals is thus understood as adaptation.

In the model below (Figure 2), a population of mosquitoes is represented throughout several generations. It encounters an insecticide (DDT) in the environment and develops resistance features, which leads to the population becoming resistant to the insecticide and surviving. The passing on of specific abilities is thus understood as adaptation.

Figure 2

Lamarckian reference model



The examination of RQ1, *How far and to what extent do students' models of evolution differ?*, is based on qualitative content analysis of students' models.

They were compared against one of the two models of reference (Figures 1 and 2), and attention was placed on these four aspects:

a) *Type of representation*: It could be a concept map, flow chart, drawing or any other type of visual representation used to explain evolution.

b) *Complexity*: Number of scenarios, elements and relationships built between them, taking into consideration how they were included and how they were related.

c) *Starting point*: first element included in the model. Specifically, the presence of the environment as the external factor or the organism as a predesigned factor offered particular points of attention.

d) *Scientific words*: concepts and phenomena included in each model, especially those related to genetics and evolution concepts (Table 1).

Regarding RQ2, what evolution frameworks underpin students' explanations when building and evaluating a model of evolution? How do these frameworks change over the course of modelling? Qualitative content analysis was carried out, focusing on students' models and the written evaluation of their models. For the identification of the evolution frameworks, we drew upon key notions included in the Lamarckian and Darwinian reference models (Figures 1 and 2). Due to the co-existence of alternative frameworks in students' ideas and confronted with the appearance of mixed models in the data, we located students' models on a spectrum of ideas between Lamarckian and Darwinian views regarding evolution theory, each model bringing particular features, as summarised in Table 1.

Table 1

Key ideas on each evolution framework

Key ideas of each evolution framework	
Lamarckism	**Neo-Darwinism**
Adaptation (after change) Inheritance of acquired characteristics	Adaptation (before change) Natural selection Mutation Genetic variability Survival of fittest

Results

Students' models of evolution in the context of explaining a real-life problem

Student's models and explanations were analysed by attending to the four aspects (a, b, c, and d) described above. They constructed models similar to diagrams and concept maps (semantic network of concepts represented in boxes, interconnected by arrows indicating the relationships among them). Table 2 summarises the results.

Table 2
Analysis of students' models

Group	a. Type of representation	b. Complexity	c. Starting point	d. Scientific words
1	Concept map	Two routes	Mutation in a population	Environment (change) Natural selection Adapt (population)
2	Flow chart	Four routes	Change in environment	Ecosystem (change) Natural selection Genetic variability Adaptation
3	Flow chart	One route	Ecosystem with living things	Change in the ecosystem Natural selection Evolution
4	Concept map	Three routes	Change in environment	Environment Natural selection Evolution Adaptation
5	Flow chart	One route	Population	Change environment Natural selection

The analysis of the type of representations points to two main approaches:

a) **Concept maps**, representation that depicts relationships between concepts (Groups 1–4)
Cause & effect relations: Group 1.
Explanatory: Group 4.

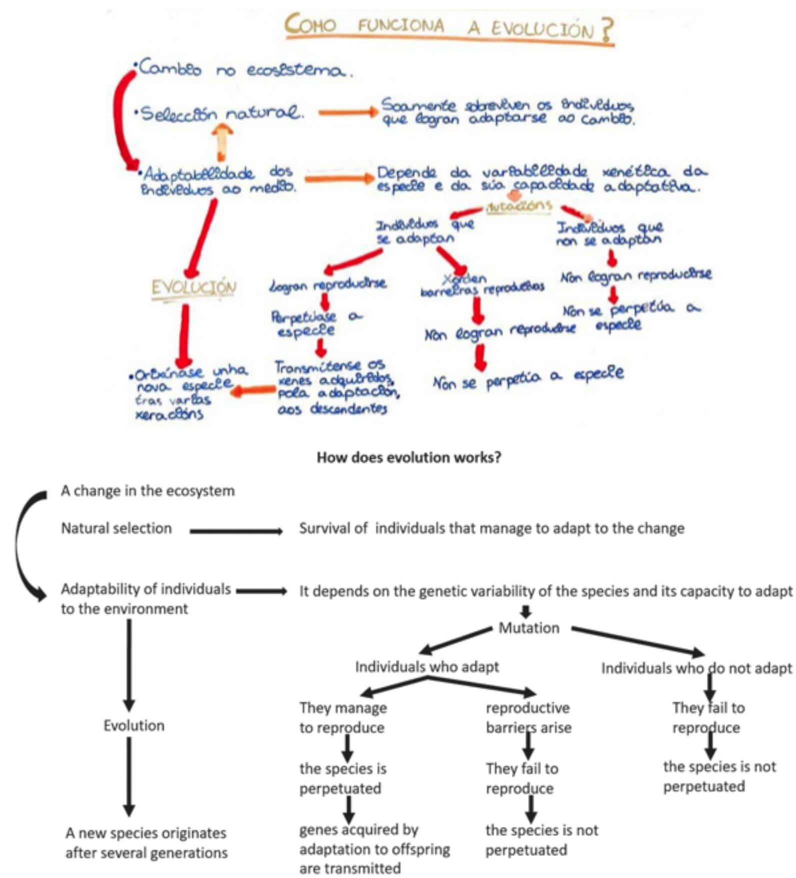
b) **Flowcharts**, representation that shows the sequence of action in a process (Groups 2, 3, and 5).

Complexity

The most frequent element is change in the environment, appearing a total of four times. In all models, a reference to the population, species, or individual appears. Across all groups, regardless of whether they had chosen a concept map or a flowchart, the layout of the models is linear (Figure 3, a & b). All groups represented the process of evolution with arrows or lines leading to one or several scenarios. For example, Figure 3a shows the representation elaborated by Group 2, in which there is a path that goes in one direction, while none of the groups considered the possibility of relating the elements backwards (as retroactive feedback) nor including relations within the environment. However, some of them included several possible routes (from Group 2 to Group 4) departing from different points in the model (e.g., in Figure 3, a & b, mutation may or may not be perpetuated across the species).

Figures 3a & 3b

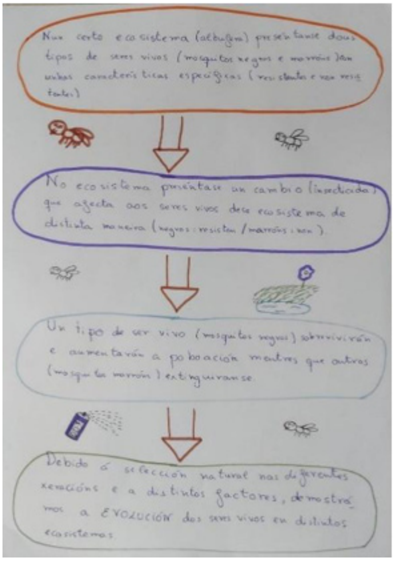
Figure 3a: Model from Group 2 (linear with 3 paths); Figure 3b: English translation.



Conversely, the model produced by Group 3 is a flowchart presenting a linear explanation of evolution (Figure 4 a & b). Their design followed four consecutive steps. The first describes the population, the second introduces the change in the environment (insecticide), the third argues which mosquitoes survive, and the fourth step is the result. In contrast, as shown in Figure 3 above, Group 2's model differentiates between the individuals that can adapt and the ones that are not able and also separates those who can adapt but do not survive.

Figures 4a & 4b

Figure 4a: Original Model from Group 3 (linear with 1 path); Figure 4b: English translation.



in a certain ecosystem (lagoon) two types of living beings appear (black and brown mosquitoes) with specific characteristics (resistant and nonresistant)

↓

A change (insecticide) appears in the ecosystem that affects living things in that ecosystem in different ways (black: resist / brown: don´t)

↓

One type of living thing (black mosquitoes) will survive and increase in population while others (brown mosquitoes) will become extinct

↓

Due to natural selection in different generations and different factors, we have shown the evolution of living things in different ecosystems

Starting point

Most groups started their model at a different point. As seen in Table 1, two groups identified the 'change in the environment' as the starting point; the other two focused on the living things/population and the last group on the mutations.

Scientific words

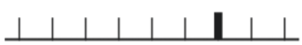
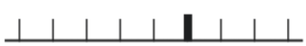
Natural selection appeared in three of the models, and adaptation also appeared in three models but not in the same ones. This may be relevant, as adaptation is a notion that can be used both from a Darwinian or a Lamarckian perspective. In the Lamarckian framework, adaptation occurs because of a change and the willingness to survive. However, in light of Darwin's ideas, adaptation may be present before any other change.

Evolution frameworks that emerge when building and assessing the models

The models and the written assessments of students' models were analysed to identify the frameworks on evolution that appeared in the two stages of the modelling process: first, while they were building the models and then when evaluating the models considering their newly acquired learning. Two main frameworks were identified: Neo-Darwinism and Lamarckian. Students' responses varied along a continuum between both frameworks as their explanations moved back and forth, drawing in explanations and ideas from either a Neo-Darwinian or Lamarckian explanation. Table 3 shows the position of students' responses on the continuum and the results of each group according to this analysis. To locate students' positions along the continuum, the number of keywords was considered. The starting point is in between frameworks, and each word/expression moves along a position on the continuum.

Table 3 summarises the results.

Table 3
Analysis of RQ2: Students' models (building and evaluating) perspective

Group	Building and explaining the model		Evaluating the model	
	Lamarckism	Neo-Darwinism	Lamarckism	Neo-Darwinism
1	– Adapt	– Mutation – Natural selection		– Mutation – Natural selection – Adapt
				
2	– Adapt – Acquired genes	– Natural selection – Genetic variability	– Inheritance of acquired characteristics)	– Darwinian
				
3		– Survival of the fittest – Natural selection		– Natural selection – Survival of the fittest
				
4		– Survival adapted		– Adapted before birth – Natural selection – Survival fittest
				
5		– Survival of the fittest		– Adapted before birth – Natural selection – Survival of the fittest
				

Building and explaining the model

From Table 3, the results show that almost all groups were closer to the Neo-Darwinism explanation rather than the Lamarckian one. In fact, none of the models showed a complete Lamarckian explanation, while one group showed mixed ideas and was neither close to Neo-Darwinian nor the Lamarckian one.

Four out of the five groups were closer to Neo-Darwinian perspectives. Moreover, they did not use many key ideas related to Neo-Darwinism; they emphasised mutation appearing prior to the change in the environment (e.g., see Group 1) and referred to mutation and natural selection as external forces acting upon the population.

For instance, for the group with mixed explanations, Group 2 included in their model: 'only surviving individuals that are able to adapt to the change', suggesting the presence of needs-based misconceptions. They identified adaptation as the result of the willingness or need to survive and change to overcome an obstacle (in this case, mosquitoes obtaining resistance against the insecticide).

Groups 4 and 5 included the survival of the fittest in their models. In their model, Group 4 wrote that the adapted are the ones that survive, while Group 5 identified the resistant to the insecticide as the ones that survive.

Group 3 is the one that included more Darwinian notions. Their last explanation said, 'Due to <u>natural selection</u> in different generations and different factors, we have shown the <u>evolution</u> of living things in different ecosystems'.

Some groups included references to a framework but showed misconceptions. Such is the case of Group 1, which included natural selection occurring before adaptation.

Evaluating the model

After instruction and the simulation activity, most of the groups moved closer to the Neo-Darwinism perspective when comparing their models to Lamarckian and Darwinist ideas.

Regarding the evaluation, we can see a shift in the ideas presented in three groups (1, 4 and 5), scoring higher in the Darwinian perspective. It is noteworthy that Group 2 is the only one that included ideas from both perspectives in their model.

> Group 2:
> 'Our model is primarily <u>Darwinian</u>. However, it is true that there are certain Lamarckist aspects that we add (such as the inheritance <u>of new characters</u> to offspring).'

This group acknowledged that in their model, there was a mixture of characteristics from the two frameworks. In the explanation, we can see that they highlighted the Lamarckian perspective, which may lead us to think that evaluating their model is more Lamarckian. However, they mentioned that they have more Darwinian characteristics, even though they did not reference them explicitly. This group showed no change between the phase of building the model and the evaluation one.

> Group 4:
> 'Natural selection makes the best adapted to the environment individuals survive, as they are genetically adapted before birth and the fittest survive.'

This group started mentioning the survival of the ones adapted when building the model and advanced to include more ideas related to the Neo-Darwinian perspective. In the evaluation, they enriched their explanation of adaptation and included natural selection in their explanation (see example below).

> Group 1:
> 'Individuals carry a genetic feature that results from a mutation that allows them to adapt to the environment.'

Natural selection and adaptation were the most common notions used by most groups. As seen in Group 1, there was a shift in how it is used 'adapt' towards a Darwinian point of view when making an evaluation. As shown in Table 3, in three out of the five groups, more key notions were mobilised when evaluating the model compared to when building it. The remaining two groups showed no change.

Discussion

Despite being one of the fundamental concepts in biology, evolution continues to be one of the most challenging and numerous difficulties have been reported (Andrews et al., 2017). This study has revealed difficulties while modelling the appearance of resistance in mosquitoes when an insecticide is present in the environment. Students' models were linear, presenting different steps to explain evolution that coincided with the original simulation in which they were engaged. Two of the models can be considered conceptual maps, one showing cause-effect relationships and the other being more discursive and explanatory. It needs to be highlighted that students were not explicitly instructed in making models, although they have previously engaged in modelling tasks. The fact that they have elaborated more descriptive than explanatory models can be affected by this, but it may also be down to their prior experience of doing schemas to summarise the contents of a unit with the teacher.

Two of the five groups presented as a starting point the change in the environment, highlighting the importance of this factor for them. Regarding the most frequent notions used in the models, adaptation and natural selection are used three times each. The analysis of these notions in students' explanations reveals that they understood the appearance of adaptation at will, which is coherent with previous results (Gregory, 2009). Aligned with Kampourakis (2013), the origin of adaptations is a commonly misunderstood process by secondary students and is related to the teleological view of evolution. Following this author, we understand that in teleological explanations, a phenomenon is framed in terms of the ultimate purpose to which it contributes. However, as recently reiterated by Kampourakis (2020), the educational problem we need to address may not be teleology per se but the underlying 'design stance', that is, whether a trait may be originally designed to perform a purpose or whether it is selected as advantageous for the organism in a particular environment. In the case of this study, students' models pointed to the possibility of shifting between and across different theories, enabling students to grapple with important questions of purpose. For example, in evaluating the model, Group 1 talked about a mutation that allows one to adapt to the environment. It has been proposed that to overcome teleological explanations and promote conceptual change, it is helpful to introduce a new conceptual framework that is more scientifically consistent with current thinking in biology (Kampourakis & Zogza, 2009).

The students seemed to encounter challenges in understanding the process of evolution due to its complexity (Mead & Scott, 2010), as well as holding needs-based misconceptions (i.e., the individual organism changes to survive), which is a common obstacle when learning about natural selection (Peel at al., 2019). This study uncovers notions from alternative frameworks on evolution (Lamarckian, Darwinism and Neo-Darwinism) that varied when building and evaluating the model, moving from Lamarckian to Darwinian explanations. After modelling, students managed to enrich their explanations on adaptation when evaluating their models in a way that is consistent with previous research (Peel et al., 2019). Three groups used the notion of adaptation more accurately, showing that this concept is a key component in their models, as well as being evidence of the theoretical frameworks behind students' explanations.

Conclusions, educational implications, and limitations

This study engaged students in the process of modelling to explain evolution of an issue in real-life contexts. The analysis shows that building models and evaluating them do not have the same cognitive requirements. We are aligned with Schwarz et al. (2009) in their suggestion that modelling activities should engage students in the process of building, explaining, assessing, and comparing models, involving them in the application of scientific knowledge as well as in the metaknowledge of the practice. Encouraging students to participate in modelling-based tasks in the classrooms may help them to overcome misconceptions about evolution; therefore, we suggest promoting modelling tasks that involve building and evaluating models to help students understand evolution.

Furthermore, engaging students in modelling evolution in real-life contexts can help us to identify students' evolutionary frameworks. As this study shows, alternative frameworks emerged when building and assessing the models. This relates to previous research, as Nehm and Schonfeld (2008) pointed out, showing that students' evolutionary explanations consisted of a mix of key notions. Attention to how these notions were applied in accordance with alternative frameworks is required. Biology instruction should attend to alternative and multiple frameworks when designing activities for evolution learning. For example, Darwin's theory of natural selection is a very general theory that is not tied to any mechanism of inheritance or cause of variation (Jablonka & Lamb, 2014), which means that evolution instruction should consider it.

Despite a growing consensus that interdisciplinary connections between disciplines are needed to better enhance students learning and understanding of evolution (Tibell & Harms, 2017), students' written explanations of natural selection did not include details or relationships to account for the genetic basis of evolution (e.g., Kalinowski et al., 2010; Bray-Speth et al., 2009). Emphasis on the relationships between genetics and evolution in modelling experiences may help students to develop more accurate explanations of natural selection as a form of retroactive rather than linear causality. It may be helpful to make explicit connections in the classroom relating the disciplines needed to enrich students' understanding of evolution, such as genetics and bio-geography, geology and history. This leads to a second implication: for biology education to embrace a plurality of interpretational frameworks, including recent calls for the active use of open-ended concepts (Brigandt, 2020) to support understanding of complex processes, which are dynamic and multi-levelled, such as evolution; and for genetics and evolution to be taught together, through processes that engage students in connecting both domains (Ageitos et al., 2019).

Some limitations need to be acknowledged. The evolution frameworks were difficult to distinguish, and the same applies to the continuum between Lamarckism and Neo-Darwinian ideas. The nature of the data analysed in this study does not allow us to have a deeper understanding of how students move back and forth between two different evolution frameworks and to what extent the process of modelling could help unravel the evolution frameworks. Further research will focus on the analysis of audio-recording to pick up on the detail of students' explanations and grapple with the methodological challenge of analysing thinking through doing to deepen our response to the research questions.

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