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# Describing changes in student thinking about evolution in response to instruction: the case of a group of Chilean ninth-grade students

Carolina Parraguez[a], Paola Núñez[a], Dirk Krüger[b] and Hernán Cofré[a]

[a]Instituto de Biología, Pontificia Universidad Católica de Valparaíso, Valparaíso, Chile; [b]Freie Universität Berlin, Berlin, Germany

**ABSTRACT**

Although much research exists of students' alternative conceptions about evolution and natural selection, the way in which these vary in time and how scientific explanations change during instruction remains to be described and understood. Therefore, the main objective of this research is to characterise the nature of the change in student thinking about evolution through the mechanism of natural selection during a six-lesson intervention with a group of ninth-grade students (14–15 years old) from a private subsidised school in Chile. The study group included thirteen students to whom a pre- and post-test was applied using the questionnaire Assessment of Contextual Reasoning about Natural Selection (ACORNS), and from whom short tasks were collected at the end of three lessons. The data were analysed using a quantitative and qualitative analysis of nine students grouped in five cases of study. The main patterns described here are the recurrence of the design teleology thinking in students, the initial use of key concepts such as mutation, survival, and differential reproduction during the trajectories, the abundance of mixed thinking during and at the end of the instruction, and the low coherence in the structure of thinking, both in time and through the different contexts analysed.

**KEYWORDS**

Natural selection; evolution; conceptual trajectories; design teleology

## Introduction

Many students around the globe hold very robust alternative conceptions about natural selection and evolution (Johannsen and Krüger 2005; Kampourakis and Zogza 2007; Nehm 2018; Deniz and Borgerding 2018; Harms and Reiss 2019; Mohammadi, Kiriazis, and Neuman-Lee 2020). These naïve or non-scientific ideas (Nehm 2018) have been described from children at preschool and primary school levels (Emmons, Smith, and Kelemen 2016; Frejd et al. 2020) to university students and biology teachers (Cofré et al. 2016; Cofré, Cuevas, and Becerra 2017).

Some authors, such as Smith (2010), have collected students' alternative conceptions about evolution, also including those that are related to the nature of science ('evolution cannot be observed, therefore, it is not science'), genetics ('all mutations are harmful') or ecology ('species' is the same as 'organism' or 'population'). In addition, Smith (2010) has classified them according to their origin, recognising errors from experience, children's psychology, school instruction and religious beliefs. On the other hand, Banet and Ayuso (2003) and Gregory (2009) coincide in recognising three main types of alternative conceptions or naïve ideas: 1) those that have to do with the evolutionary history of species diversity or the macroevolutionary process (e.g. 'dinosaurs and

**CONTACT** Hernán Cofré hernan.cofre@pucv.cl

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humans living together'; 'evolution always goes towards perfection or towards greater complexity'); 2) those that have to do with the scientific status of the idea of evolution ('studies in evolution do not follow the scientific method'; 'evolution is just a theory'); and 3) those that are directly related to the microevolutionary mechanism of natural selection ('use and misuse'; 'change due to the need generated by the environment'). In the same vein, Nehm (2018) defines alternative conceptions as non-normative ideas, which are different from normative scientific ideas recognised by scientists in evolutionary explanations (e.g. mutation, inheritance, or fitness). Research done by Nehm and his collaborators has shown that alternative conceptions often mixed with normative scientific ideas in students' evolutionary explanations. Furthermore, according to their work, students' thinking about evolution is context dependent (e.g. trait, taxa or hierarchical level; Nehm and Ha 2011) and can be analysed according to its composition (kind of element included in the explanation, for example need alternative conception or scientific aspects such as mutation), structure (the way in which students connect these elements) and coherence (the maintenance of an explanation structure in different contexts; Nehm and Kampourakis 2016).

Despite the large body of literature devoted to reviewing students' thinking about natural selection, there are very few studies that focus on temporally describing how students' ideas change during instruction (e.g. Zabel and Gropengiesser 2011). Most studies have reported results from one moment: before, during or after instruction (e.g. Kampourakis and Zogza 2007; Nehm and Ha 2011; Cofré et al. 2016; Frejd et al. 2020). Other studies have compared thinking of secondary students that differ in age (e.g. To, Tenenbaum, and Hogh 2017) or changes in students' thinking in pre and post designs (e.g. Emmons, Smith, and Kelemen 2016; Cofré et al. 2018a) or including delayed assessments (e.g. Asterhan and Schwarz 2007).

In this context the currently reported study aimed to describe the development of students' thinking about evolutionary change that ninth grade students present during instruction on the mechanism of natural selection. The different states of the students' thinking are characterised following the nomenclature developed by Nehm (2018) and the trajectory of the group of students is presented in three contexts (human, animal, and plant), combining the landscapes described by Zabel and Gropengiesser (2011) with the most recurrent names in the classifications of the type of evolutionary explanation given by students (Nehm 2018). It is expected that this new methodology to describe the change in the evolutionary thinking of students will make a contribution towards the search for explanations about how scientific thinking is built on this topic in students.

## Theoretical background

### *Conceptual change and natural selection instruction*

According to the literature on conceptual change and instruction, the traditional view proposed that this change can be accounted for by the effect of cognitive conflict on scientific knowledge reconstruction (Posner et al. 1982; see also Vosniadou 2013a). Thus, when contradictory views are explicitly juxtaposed, students become aware of their own alternative conceptions, prompting their review with the consequent knowledge restructuring or the replacement of incoherent ideas with accepted ones. However, this simplified view lacks not only social and situational factors, but also affective and motivational ones that also influence the knowledge restructuring (Chi, Kristensen, and Roscoe 2012; Vosniadou 2013a, 2013b). According to Vosniadou (2013a; 2013b), science educators need to move from thinking of conceptual change as involving single units of knowledge to systems of knowledge that consist of complex substructures that may change gradually and in different ways.

Regarding the issue of conceptual change and evolution, some authors have proposed that to help students develop an understanding of evolution and natural selection, teachers need to guide them to confront their alternative conceptions, and they must experience the failure of their intuitive theory to adequately explain the evidence (Kampourakis and Zogza 2007; Nehm and

Kampourakis 2016). However, empirical results have shown that understanding the process of evolution and the mechanism of natural selection requires a more complex endeavour (Chan et al. 1997; Chi, Kristensen, and Roscoe 2012; Evans et al. 2012). For example, Chan et al. (1997) found that the effect of conflict, especially among peers, on evolution knowledge, is mediated by the deeper knowledge-building activity (and sophistication of the discourse processes) that conflict prompts. On the other hand, because evolutionary theory is probably one of the most counterintuitive ideas in science, Evans et al. (2012) proposed that understanding it requires a 'radical' conceptual change approach: students must switch from a naïve psychological explanation that uses an anthropomorphic argument to a naturalistic explanation that avoids purpose and endorses the idea that species can undergo significant change. To address this monumental challenge, Evans et al. (2012) proposed a developmental learning progression that included four levels: 1) anthropomorphic reasoning external agent; 2) want-based reasoning intrinsic cause, 3) need-based reasoning, 4) natural selection, and 5) evolutionary origins. But how does the shift from need-based reasoning to natural selection thinking occur?

### *From a list of alternative conceptions to student thinking framework of natural selection*

In the recent past, the study of students' thinking about natural selection has moved from the identification and classification of alternative conceptions (Gregory 2009; Cofré et al. 2016; Nehm 2018) to the description and understanding of how this non-sequential or emergent process (Chi, Kristensen, and Roscoe 2012) is explained (Zabel and Gropengiesser 2011; Evans et al. 2012; Nehm and Kampourakis 2016). For example, some studies have shown that in the transition between a need-based reasoning and true natural selection thinking, high school students mostly used the concept of variation and differential survival to explain evolution (Evans et al. 2012). There was a similar finding by Nehm and Ha (2011) when they studied undergraduate biology majors' thinking about evolution. Variation and its causes, and differential survival and reproduction, were the more frequent scientific elements in college students' responses. In accordance with this and other research carried out by the same study group, Nehm and Kampourakis (2016) propose to recognise not only the different components of students' thinking (e.g. scientific, and non-scientific elements), but also their structure and coherence (see also Nehm 2018). Analysing the composition of students' explanations, Nehm and Kampourakis (2016) established that a student can combine need-based reasoning with the scientific ideas of mutation and inheritance to build a mixed model response.

On the other hand, there are few studies on students' thinking about evolutionary change over time and the different trajectories that students carry out in the learning process. An interesting exception is the study of Zabel and Gropengiesser (2011), who show that learning to explain evolution is a very individual process where the students depart from several distinct ideas and take different trajectories: description to need-based reasoning; need-based reasoning to simple Darwinian or simple Darwinian to complete Darwinian thinking. The study identified five conceptual frontiers, each of them marking one major learning task. Thus, the authors 'visualised' learning progress of the students as learning trajectories on a conceptual landscape.

### *Rationale and research aim*

Although both in Chile and the rest of the world there are studies on students' alternative conceptions on the topic of evolutionary change (cf. Nehm 2018 for a review) and on the efficiency of certain strategies for teaching evolution (e. g. Cofré et al. 2018a), there are very few studies about the development of students' thinking through instruction (Zabel and Gropengiesser 2011). Therefore, the objectives of this study were:

- Describe a nomenclature and a unified methodology that enables characterisation of the process of change in students' thinking about evolution

- Characterise, through a conceptual landscape of students' thinking, the different trajectories of the students' learning about evolution.
- Understand how change in the composition structure and coherence of students' thinking about evolution may occur in a group of ninth-grade students, before, during and after instruction.

## Methods

### *Study design and participants*

The present study corresponds to a descriptive investigation that includes both quantitative and qualitative methods to characterise evolutionary thinking in a group of 25 ninth grade students (14–16 years old) before, during and after instruction. The students attend a private subsidised school in the region of Valparaíso, Chile. The study included the analysis of 13 students for quantitative data (only pre and post-test) and nine students for qualitative data (pre and post-test and three other formative assessments during instruction), since only this sample carried out all the learning activities. All students that participated in the study gave their own, and their parents', written permission. The low socio-economic level or high vulnerability index of the students' school, in part, explains the great absenteeism during the implementation of the lessons. According to the new curriculum in Chile, ninth grade students have not reviewed aspects of genetics before learning evolution, which has been described as important knowledge when it comes to understanding natural selection (Mead, Hejmadi, and Hurst 2017; Homburger et al. 2019).

### *Instruction*

In the design of the intervention, the conceptual change-theory was considered (Posner et al. 1982; Vosniadou 2013a, 2013b). This focuses on analysing learning pathways from students' preconceptions before instruction about scientific concepts (Duit 1999). The activities were designed based on active and student-centred learning strategies as suggested in the evolution education literature (Glaze and Goldston 2015; Harms and Reiss 2019). Specifically, it included the inquiry and work with real examples of evolution of animal species, as well as modelling natural selection, and the nature of science, which have been suggested as key elements to challenge different preconceptions related to evolution (Cofré et al. 2018a; Scharmann 2018). Table 1 shows the main characteristics of the lessons that were included in the intervention.

### *Instruments and data collection*

Before the intervention, students answered a modified version of the Assessment of Contextual Reasoning about Natural Selection (ACORNS), one of the most used questionnaires in the current literature on evolution education, to assess students' ideas about natural selection (Nehm et al. 2012). The format of ACORNS items is as follows: 'How would biologists explain how a species of X [with or without a trait] evolved from an ancestral Y species [without or with]?' Following the suggestion of the authors, we use ACORNS as a base, including one original question (How would biologists explain how a living rose species with thorns evolved from an ancestral rose species that lacked thorns?), and three new questions following the same structure (e.g.: i] How would biologists explain how human being species lacking body hair evolved from an ancestral human-like species that had body hair?; ii] How would biologists explain how a living bat species lacking wings evolved from an ancestral mammal species that lacked wings?; iii] How would biologists explain how a living mouse species with black hair evolved from an ancestral mouse species with white hair?). We used these four items differing in surface features (e.g. animal vs. plant, trait gain vs. trait loss) to assess students' knowledge. The same instrument has been applied before in the context of

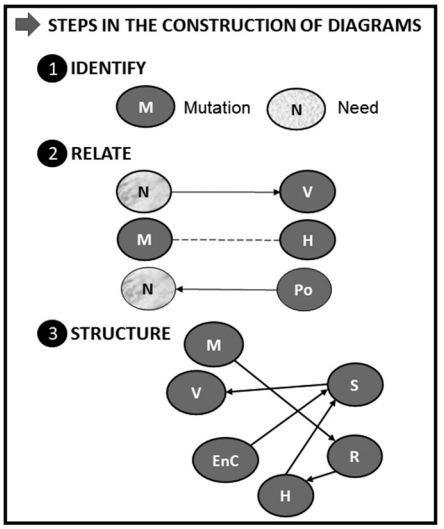
**Table 1.** Lesson sequence for teaching evolution with a description about instructional strategies and activities.

| Lesson's sequence | Context – content | Instructional Strategies | Lesson task- Context |
|---|---|---|---|
| Pre – Test | ACORNS pre-test | - | Contexts: Animal – Plant – Human |
| Lesson 1 | Evolution and the origin of Chilean biodiversity | Lecture and discussion about how students think biodiversity arises | - |
| Lesson 2 | Activity about evolution of dogs (Núñez et al. 2022). | Model-based and inquiry-based instruction including analyses of research data | - |
| Lesson 3 | Activity about Rock pocket-mice (Lucci and Cooper 2019). | Inquiry-based instruction including analyses of research data | - |
| Lesson 4 | Activity about Evolution of lactose tolerance in humans (Jördens and Hammann 2019). | Model-based and inquiry-based instruction | Context: Human<br>Topic: Human Arsenic adaptation in indigenous Chilean people |
| Lesson 5 | Activity on orchid evolution in Chile | Inquiry-based instruction including analyses of research data | Context: Plant<br>Topic: thorns as adaptation to drought in cactus |
| Lesson 6 | Formative assessment | Students answer a formative assessment about all topics reviewed in the sequence | Context: Animal<br>Topic: Los Degúes in Chile. |
| Post-test | ACORNS post-test | - | Contexts: Animal – Plant – Human |

Chilean secondary students with good reliability and validity in Spanish (Cofré et al. 2018a, 2018b). In addition, evolutionary ideas of each student were collected at the end of lessons four, five and six through a formative assessment. These evaluations included two questions. First, what did you learn today? Additionally, a second question with the same structure of ACORN instrument (e.g. in the lessons 5 [T3]: How do you explain how a species of cactus evolved from an ancestral plant without thorns?). These questions were analysed in the same way as the pre and post-test since they included similar questions.

### *Data analysis*

A modification of the rubrics developed by Nehm et al. (2012) was used to score the ACORNS responses (Cofré et al. 2016, 2018a, 2018b). From the open questionnaire responses, ACORNS could determine both the correct items in the answers and the presence of alternative conceptions about the mechanism of evolution by natural selection. The rubrics included detailed scoring information for 11 key concepts (accurate ideas) and eight alternative conceptions or naïve ideas (Nehm 2018). Key concepts (mutation, variation, heredity, population, environmental change, reproduction, survival, competence, limited resources, change in gene frequency, origin of new species) scores for each item could range from 0 to 11, and alternative conception scores could range from 0 to −8. The maximum key concepts score across all four items could be 44, and the maximum alternative conception score could be −32. Participants' responses that incorporated aspects from more than one category were classified as mixed responses. The alternative conceptions recognised were teleology (change by purposeful need), Lamarckian, Amechanistic (evolutionary change explained because of different evidence [fossil, genetic, or morphological], not by a mechanism), Chimerical (new species originate from the mixture of two existing species), and evolution at individual level (See Gregory 2009; Zabel and Gropengiesser 2011; Cofré et al. 2016; Nehm 2018 for a more detailed information about different alternative conceptions recognised in the literature).




The diagrams are constructed in a temporary way according to the student's explanation, following three steps:

1. Identify correct (white letter) and incorrect (black letter) concepts.
2. Relate the concepts with arrows, where the temporal sequence of the explanation indicates the direction of the date. If in the explanation the concepts are only named and not related, the concepts are joined with a dotted line.
3. Structure the explanation using as a core basis the key concepts associated with natural selection (mutation, variability, survival, reproduction and inheritance) and incorporating other concepts that arise in the explanation whether they are correct or incorrect.

- The scheme composition is given by the concepts used in the exxplanation.
- The structure of the scheme is built based on the components and their relationships indicated by arrows.
- Coherence is obtained by comparing the different structures built in each answer given by the student.

**Figure 1.** Steps in the construction of the diagrams of the students' explanations on evolution. Capital letters means: M = mutation, N = need (teleology), V = variation, H = heredity, Po = Population, EnC = environmental change, R = reproduction, S = survival.

Two authors independently coded 104 responses for the presence or absence of naïve ideas and key concepts. Mean inter-rater reliability values were measured using Kappa ($\kappa = 0.94$; $\kappa = 1.0$) in the pre-test (naïve ideas and key concepts respectively) and ($\kappa = 0.97$; $\kappa = 0.96$) in the post-test (naïve ideas and key concepts respectively). Discordant scores were resolved via deliberation between the two researchers, leading to a set of consensus scores for all concepts. For a more in-depth description of the development of ninth-grade students' thinking about change by natural selection, five diagrams were created based on the composition-structure-coherence framework developed by Nehm and Kampourakis (2016; cf. Nehm 2018). Composition refers to accurate or naïve ideas used to explain the evolution of species in a lesson task or ACORN question. The structure of the response refers to the different ways in which the ideas are connected. Thus, an explanation can be formed by the same ideas, but may be connected differently. Finally, coherence exists when an explanation maintains the same structure in different contexts. Figure 1 explains the steps that were followed to generate the explanation diagrams for each student's response.

Regarding the concepts that make up the diagrams, these were built and included temporally. The ideas are identified as the student names the components and relates them to their explanation. These components were identified by their initial, for example: V = variation or H = heredity (Figure 1). These components are identified as correct or incorrect. The correct ones or key concepts are represented by a dark grey circle, while the incorrect or naïve ideas are represented by the light grey circle. Regarding the structure of the diagrams, those concepts that are taught as key concepts of the mechanism of natural selection: variation, reproduction, differential survival, and heredity, are grouped in the centre. Then, other accurate (population, environmental change, selective pressure) or naïve (need, use and disuse, anatomical comparison, chimerical) ideas are incorporated around the first core components. To evaluate the coherence of the evolutionary thinking of the students, the structure of the explanation was compared in three different contexts: human, plant, and animal.

In addition to performing this analysis per student, three general conceptual landscapes of the trajectories of the students' thinking in the contexts were constructed, modifying the proposal of Zabel and Gropengiesser (2011). For the creation of these conceptual landscapes, the categories already described in Cofré et al. (2016), that are consistent with the ideas recognised by the framework of Nehm (2018), were used.

## Results

### *Quantitative analysis of students' thinking*

Before the instruction, most students explained evolutionary change via purposeful need or teleology or simply did not know how to explain it. Genuine Lamarckian explanations (use and disuse) were least represented (mostly in a human context), but a few students explained evolution as the reproduction of two different species or Chimerical (Figure 2). The context that presents the greatest diversity of alternative conceptions is the human one. However, after instruction, many students in the class improved their knowledge and were able to explain evolutionary change including more key concepts related to the mechanism of natural selection, with (mixed) or without (Darwinian) naïve ideas. Regarding the context of the question, the students perform better when the response about evolutionary change is made within an example of animal evolution.

When the focus of analysis shifts from students' thinking to the concepts or ideas used, there are differences in the frequency with which the correct ideas are used after instruction. Regardless of the context of the question, the correct concept most used in post-test explanations was mutation. Depending on the context, other correct concepts are also used with high frequency such as: variation and survival in an animal context; survival and population in a plant context; and heredity and survival in human context (Figure 2).

### *Qualitative analysis of some students' thinking*

Next, we describe five cases that correspond to the different trajectories followed by the explanations of nine students. The cases are; Case 1 (Good change, few key concepts, and high coherence, including student S1); Case 2 (Good change, many key concepts, and medium coherence, including

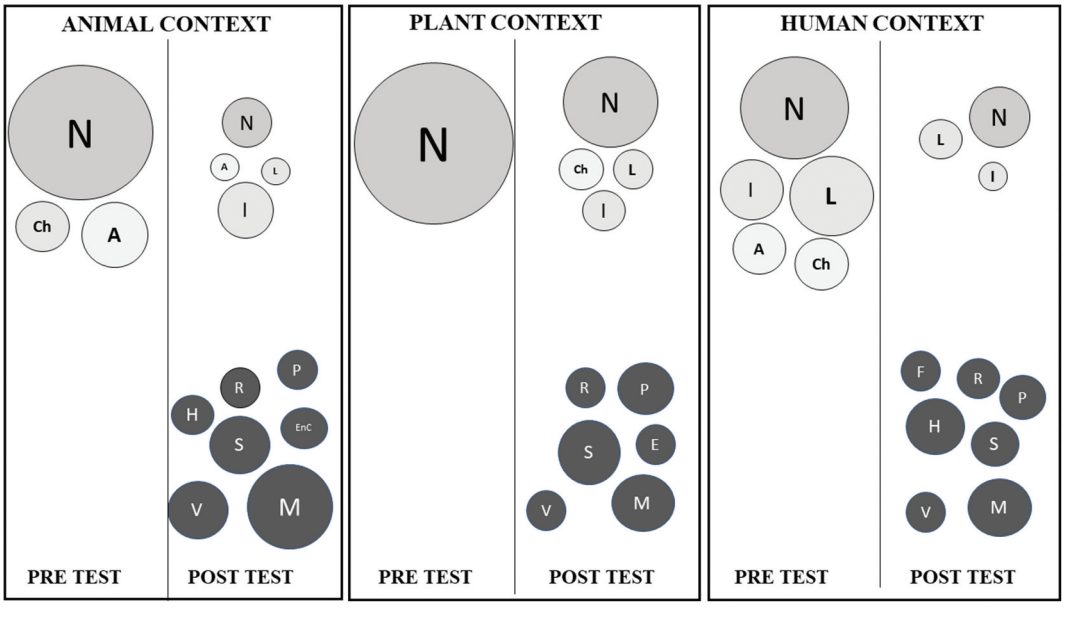



**Figure 2.** Frequency of total concepts used by 13 ninth-grade students in each context (animal, plant and human) before and after instruction. The size of the circles indicates how often the concept was used (% of the students that include each concept). For example, for Need (N) is: 75% in pre-test animal context, 12% in post-test animal context, 100% in pre-test plant context, 33% in post-test plant context, 42% in pre-test human context and 17% in post-test in human context. Capital letters mean: Ch = Chimerical; I = Individual evolution; A = Amechanistic response; L = Lamarckian. M = mutation, N = need (teleology), V = variation, H = heredity, Po = Population, EnC = environmental change, R = reproduction, S = survival.

student S2); Case 3 (Small change, few key concepts, and low coherence, including students S3 and S6); Case 4 (Small change, many key concepts, and low coherence, including student S4); Case 5 (no change, few naïve ideas and medium coherence, including students S5, S7, S8 and S9).

### *Case 1 (Good change, few concepts, and high coherence)*

In Figure 3, it can be recognised that, at the beginning (pre-test) student S1 did not present an explanation about evolutionary change in the human and plant contexts. In the animal context, S1 explained the change through the organism's need to change voluntarily to survive in a new environment: *'because the mice need (N) to adapt to their new environment'* (See also Figure 1 for understanding steps in the construction of the diagrams). When the instruction begins, it is interesting to note that S1 does not use the need alternative conception already in lesson 4 (Table 1), in which he incorporates 4 key concepts to explain the change in humans (Figure 3). Not only in terms of number, but also in terms of identity of the concepts used in his explanations, S1 seems to maintain almost the same structure, displaying coherence throughout the three contexts of evolution. Through the explanations, the most used key concepts were mutation (4), change in population (3) and differential survival (3). The great coherence that exists between the explanation of the human context and that of the animal context is remarkable, since the same four elements are incorporated and two of the 4 interactions between them are repeated. In his last assignment of lesson 7 (T4) the student mentioned: '*The mechanism is natural selection; with the change the light-coated rodents (Po) were exposed to predators and the light-coated rodents decreased and the dark-coated rodents (V) increased (S) because they reproduce (R)*'. Despite the development of the explanation through the instruction, at the end (post-test) S1 only relates evolutionary change to one key concept: mutation as a cause of variability in the population. This occurred in all three contexts.

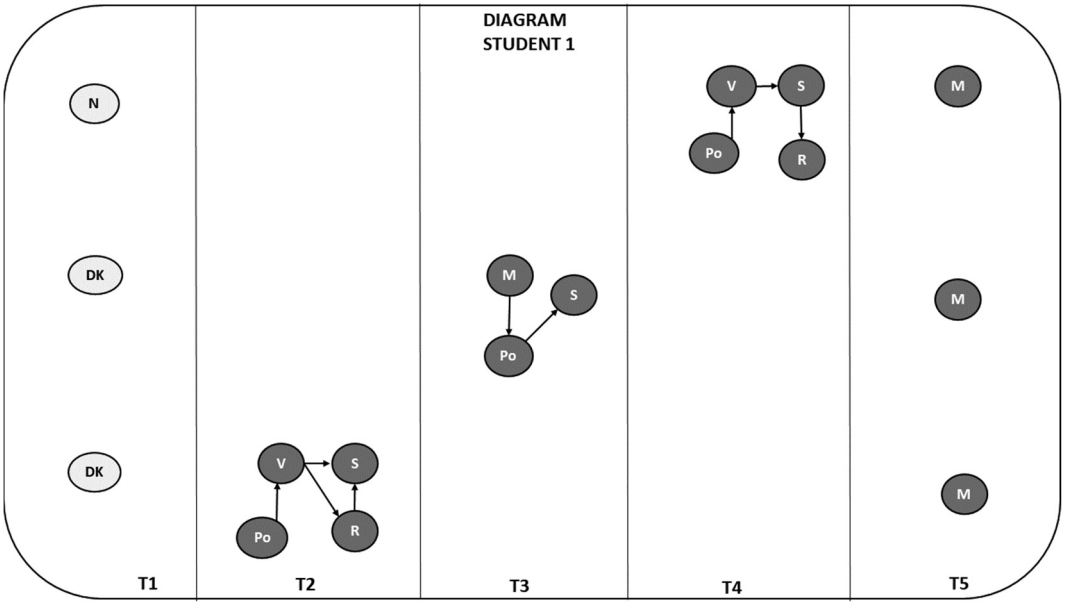



**Figure 3.** Diagram of the change in the composition and structure of the explanation of a ninth-grade student (S1) on evolution in three contexts. Key Concepts: V = variation, S = survival, Po = population, R = reproduction, M = mutation. Naïve ideas: N = need, DK = Do not know. In the **upper part** of the figure, diagrams of **animal context** are shown, in the **middle**, diagrams of **plant context** are shown and in the **lower**, diagrams made in the context of **human evolution** are shown. T1 = Pre-test; T2 = lesson 4; T3 = lesson 5; T4 = lesson 6; T5 = Post-test.

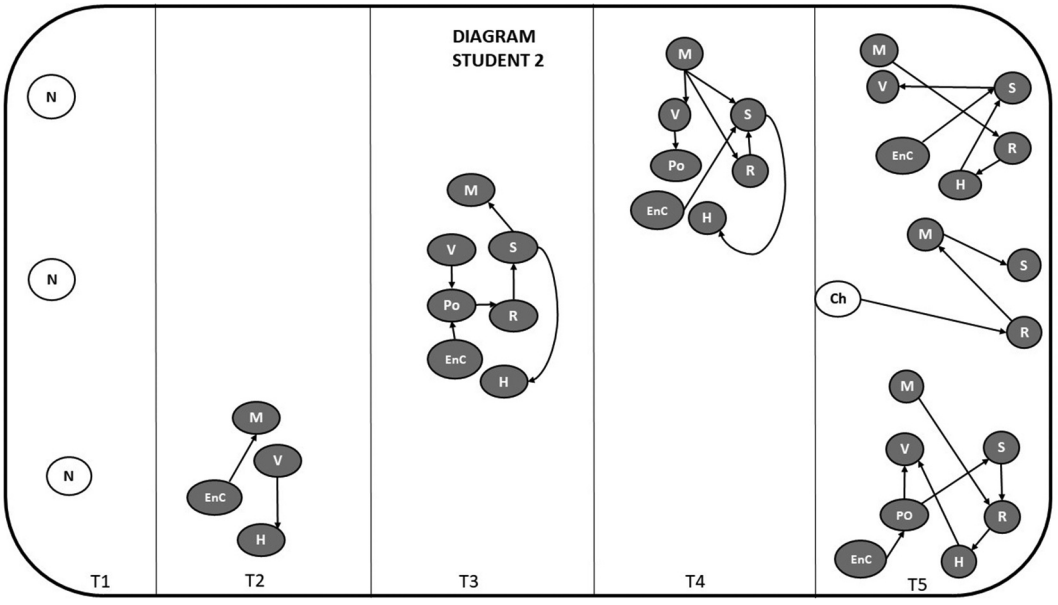



**Figure 4.** Diagram of the change in the composition and structure of the explanation of evolution in three contexts of a ninth-grade student (S2) of a subsidised private school in Valparaíso. Key Concepts: V, S, Po, R, M, as in Figure 3. H = Heredity; EnC = Environmental change. Naïve ideas: N = need, Ch = Chimerical. Question's contexts and T are the same as in Figure 3.

### *Case 2 (Good change, many key concepts, and medium coherence)*

In this case, S2 begins by explaining evolutionary change in the three contexts through need (Figure 4). However, once the instruction has begun, the student gradually incorporates key concepts. In lesson four (T2), he includes four concepts and in the following lessons he included seven. It should be noted that, at this time of the intervention (lessons 4, 5 and 6) the student does not use alternative conceptions to generate his explanations in any context (Figure 4). Of the 34 key concepts used in the nine explanations, 6 correspond to mutation, that is, it was a central element in the structure of explanations, as well as variation, inheritance, survival, differential reproduction, and environmental change, used 5 times. In T3, S2 gave the following explanation regarding the evolution of the cacti: '*There was a variability (V) in the population (Po) with respect to the size of the spines of the cacti, which had a larger size, perhaps supported by the selective pressure of the animals(EnC), they reproduced (R) and survived (S) due to the mutation (M), which transferred the DNA to the next cacti until today (H)* '. Although these components are maintained in the structure of most of the explanations, great coherence was neither observed in the relationships between components, nor across the different contexts.

### *Case 3 (Small change, few key concepts, and low coherence)*

Figure 5 shows that the explanations of student S3 only include 6 key concepts and 4 wrong ideas. In the pre-test, the student declared not knowing how the evolution process occurs. This lack of knowledge is replaced in the explanation of lesson 4 (T2), by a mixed explanation that included need and variation: '*Through evolution, people have to adapt (N) to the presence of arsenic. Some are more resistant since they have variability (V)*'. The explanation by need is incorporated again at the end of lesson 5 (T3), in the plant context task. This explanation by

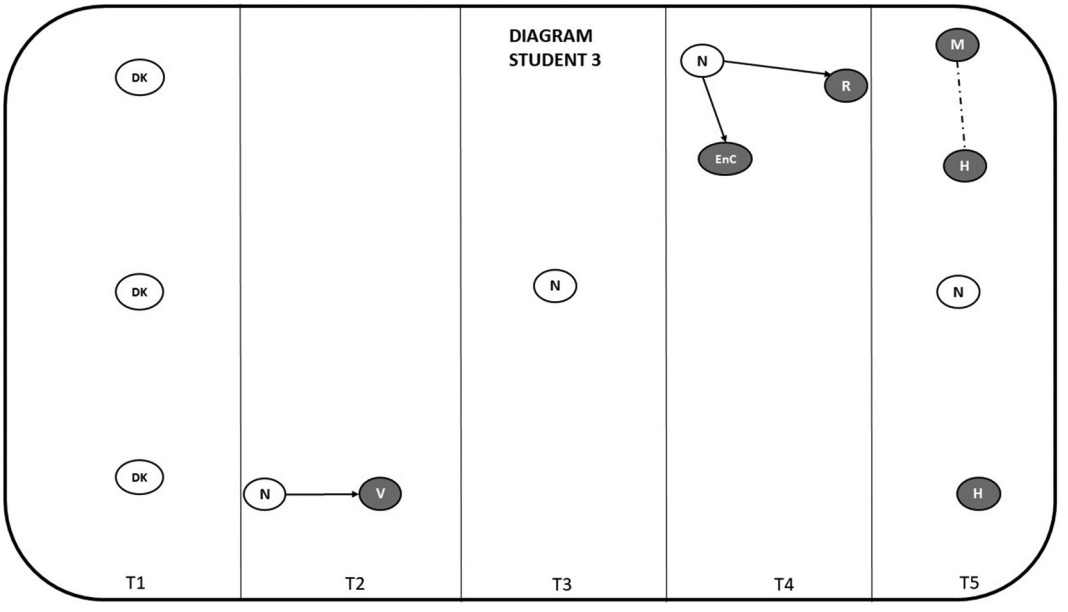



**Figure 5.** Diagram of the change in the composition and structure of the explanation of evolution in three contexts of a ninth-grade student (S3) of a subsidised private school in Valparaíso All concepts are the same as in Figures 1 and 3. Question's contexts and T are the same as in previous Figures.

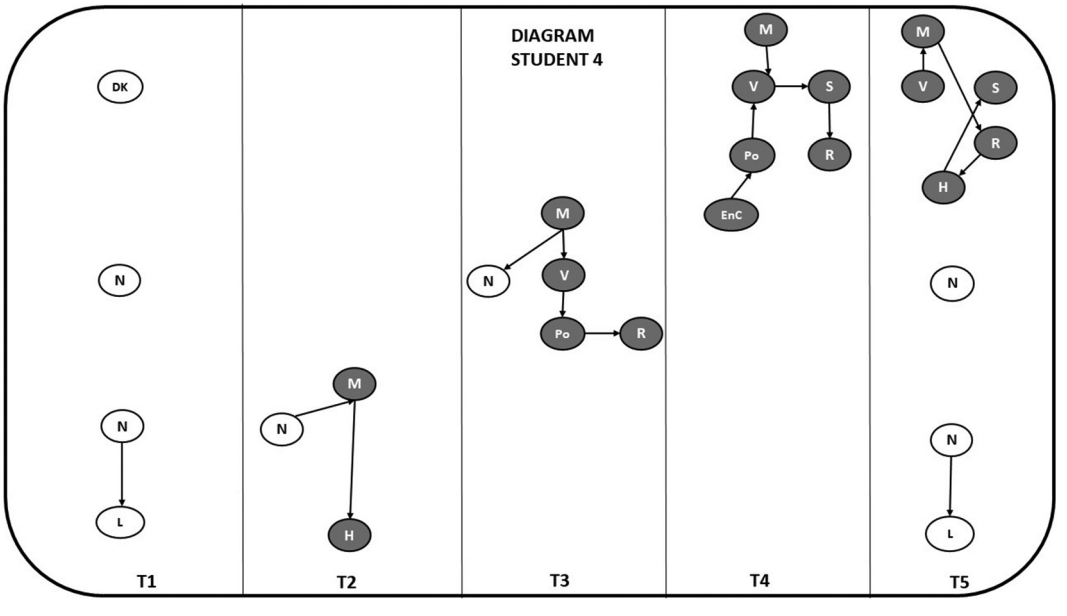



**Figure 6.** Diagram of the change in the composition and structure of the explanation of evolution in three contexts of a ninth-grade student (S4) of a subsidised private school in Valparaíso. All concepts are the same as in Figures 3–5, except L = Lamarckian. Question's contexts and T are the same as in previous figures.

purposeful need is consistent up to the post-test in the plant context, whereas, in the post-test questions of animal and human contexts, the S3 student responds incorporating inheritance and mutation, but without including alternative conceptions.

### *Case 4 (Small change, many key concepts, and low coherence)*

Figure 6 shows that the explanations of student S4 include 17 key concepts and 8 wrong ideas. In the pre-test, the student explains the evolution process by purposeful need and Lamarckian use and misuse of traits. During lessons (T2 and T3), student S4 created mixed explanations that included need and some key concepts such as mutation: *'I would explain this by a mutation (M) that allows it to make that change. It develops this to protect (N) itself from the possibility of being eaten by other animals, pricking them. The population (Po) varied (V), with different sizes of spines, which have reproduced (R) opposite to the small spines that have ended little by little'*. In the last lesson, the explanation in the animal context did not include any alternative conceptions and incorporated six key concepts. Therefore, the number of key concepts increased through the lessons. However, the great coherence present in the explanation of the animal context is not maintained in the other contexts of the post-test questions, where, both alternative conceptions of necessity and Lamarckism explanations reappear (Figure 8).

### *Case 5 (no change, few alternative conceptions and high coherence)*

In this case, we include all students that did not change their thoughts at all (S5, S7, S8 and S9). One example of this kind of development was student S8 (Figure 7). At the beginning, S8 did not present an explanation about evolutionary change in the animal and plant context, but in the human context, S8 explained the change through a Chimerical alternative conception by the reproduction between different hominid species: ' . . . *because they have mixed with other species (Ch) and that is how they evolved to us* . . . '. During lessons (T2, T3, T4), S8 created different explanations that included purposeful need without including any key concepts. In a similar pattern, students S5, S7, and S9 also included mostly need to explain evolutionary change in the lesson's tasks. In the case of S8, a few key concepts appear in the post test explanations, creating mixed responses in which need is combined with change in population and differential survival.

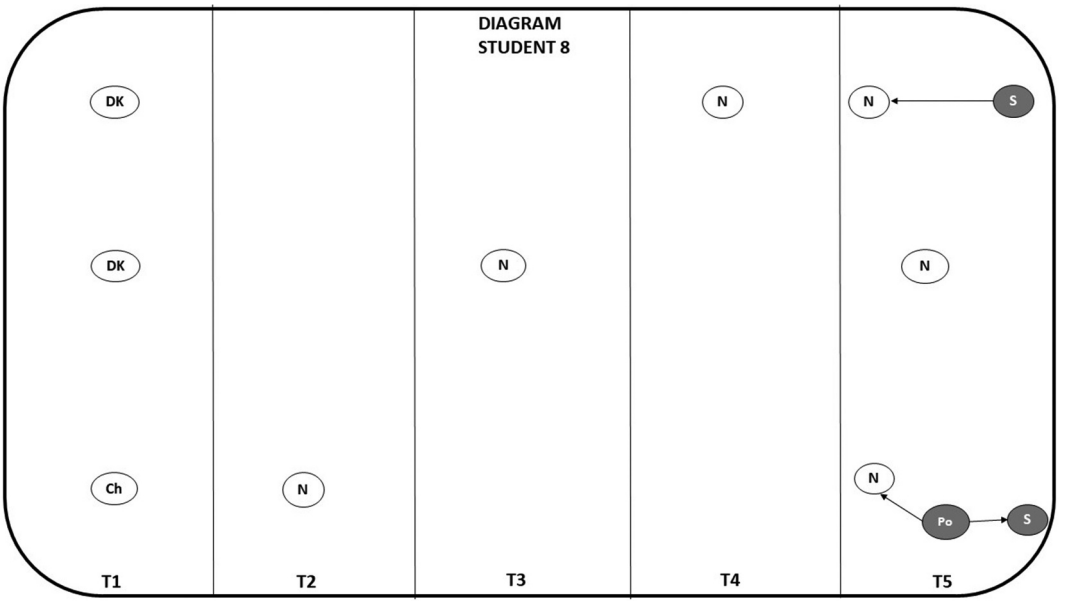



**Figure 7.** Diagram of the change in the composition and structure of the explanation of evolution in three contexts of a ninth-grade student (S8) of a subsidised private school in Valparaíso. All concepts question's contexts and T are the same as in previous Figures.

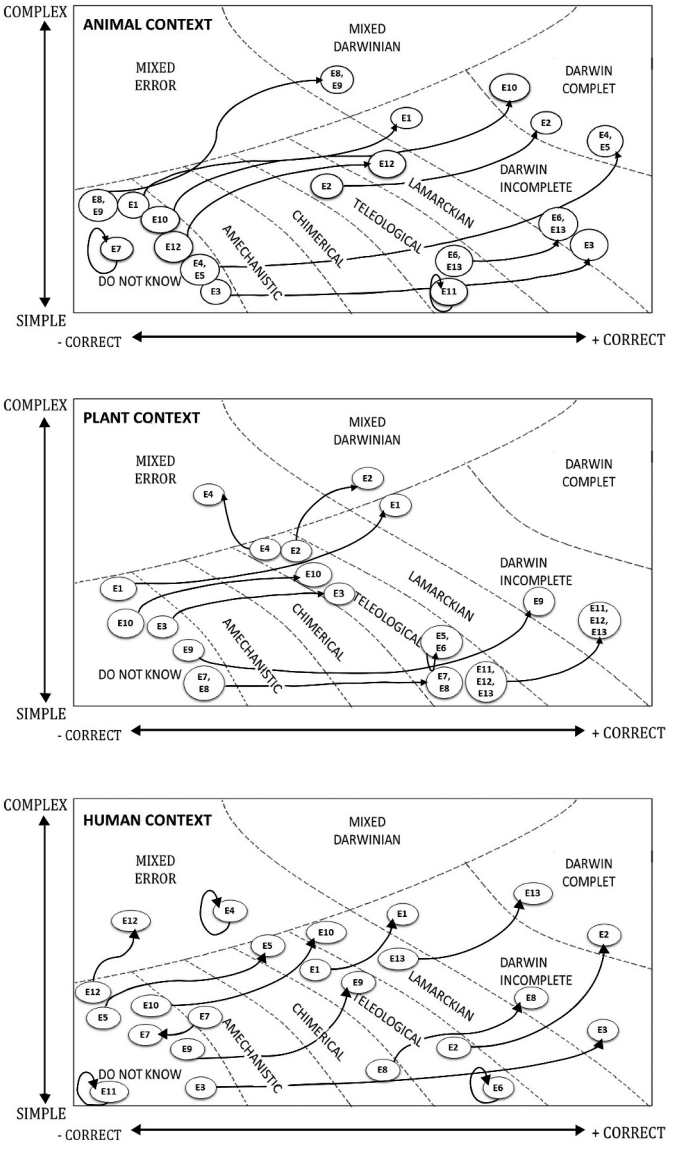



**Figure 8.** Landscape of the explanations about the evolutionary change in thirteen students from a private subsidised school in Valparaíso, (modified from Zabel and Gropengiesser 2011). The areas within the landscapes follow the nomenclature of alternative conceptions and types of responses used in previous publications (e.g. Cofré et al. 2016, 2018a; Nehm 2018).

## *Conceptual landscapes of students' ideas about evolutionary change*

One way to synthesise both the quality of the explanation of each student, as well as their trajectory from the beginning to the end of the instruction, is through the generation of conceptual landscapes like those developed by Zabel and Gropengiesser (2011). Figure 8 shows the trajectories of each student's explanations for each of the three contexts. By analysing these three conceptual landscapes we can recognise patterns of similarities and differences among them. A first similarity is that, regardless of the contexts, at the beginning of instruction more than half of the students were completely unaware of how to explain evolutionary change. On the other hand, the rest of the group, in general, explained the evolution of the species through need. One last thing in common that the trajectories have in all three contexts is that most of the students who do not know how to

explain evolutionary change at the beginning, end up explaining it through some alternative conception, while many of those who begin by explaining the change through a naïve idea, end up explaining it with Darwinian answers, whether they are complete, incomplete, or mixed with naïve ideas. One of the differences that can be found between the contexts is that, in the animal context, students seem to achieve better explanations at the end of instruction.

## Discussion

### *Use of scientific concepts and naïve ideas in student' thinking*

Regarding the analysis of students' alternative conceptions before, during and after the intervention, it could be observed that in all contexts the idea most used is intentionality, need or teleology, which confirms what the literature has shown in the last 15 years (e.g. Kampourakis and Zogza 2008; Nehm and Ha 2011; Cofré et al. 2016, 2018a; To, Tenenbaum, and Hogh 2017; Nehm 2018). More specifically, and according to Kampourakis (2020), the most frequent alternative conception was the design teleology (internal or external); that is, something exists because its functions contribute to the fulfilment needs of its possessor or because of an external agent's intention such as environmental change. Much less frequently, alternative conceptions such as: 'Lamarckian', 'Chimerical', or 'individual organisms evolve', were also observed (Zabel and Gropengiesser 2011; Cofré et al. 2016; To, Tenenbaum, and Hogh 2017; Nehm 2018; Mohammadi, Kiriazis, and Neuman-Lee 2020). As has been described in previous studies, human (Pobiner et al. 2018) as well as plant contexts (Nehm and Ha 2011; To, Tenenbaum, and Hogh 2017), seem to be more difficult settings for students to incorporate key concepts of natural selection in their responses. A similar trend was found by To, Tenenbaum, and Hogh (2017), who reported that secondary students (12 to 16 years-old) were better able to incorporate key concepts in explanations about animals' evolution than in chimps/humans, and algae examples. During and after instruction, students partially abandon their alternative conceptions, generating for the most part, mixed explanations (Nehm and Schonfeld 2007; Nehm and Ha 2011; Chi, Kristensen, and Roscoe 2012; Cofré et al. 2016; To, Tenenbaum, and Hogh 2017). In summary, there was little improvement in understanding the mechanism of natural selection unlike in some previous studies (e.g. Chi, Kristensen, and Roscoe 2012). However, key concepts more used in students' explanations in this study such as mutation, survival, and variation, coincide with previously reported findings (e.g. Nehm and Schonfeld 2007; Kampourakis and Zogza 2008; Nehm and Ha 2011; Opfer, Nehm, and Ha 2012). According to Vosniadou (2019) students can understand and assimilate scientific concepts learned during lessons in their pre-existing mental structuring, being unaware that there is a conflict between the scientific and the non-scientific, generating mixed or synthetic mental models of the phenomenon to be studied. In the case of evolution by natural selection, this hypothesis appears to be true (Nehm and Schonfeld 2007; Chi, Kristensen, and Roscoe 2012; Nehm and Kampourakis 2016; Cofré et al. 2018a).

### *Changes of components and structures of students' thinking about evolution*

According to Nehm (2018), the composition-structure-coherence framework can be useful for monitoring changes in students' thinking in response to instruction. In this study, we recognise five cases of development of student thinking. Analysing all cases, we identified that very few students achieve conceptual change, reaching a complete Darwinian idea, and many of them even maintain their alternative conceptions throughout the teaching process.

In most cases, explanations show a quite simple structure, and a low level of coherence among contexts. As Nehm and Ridgway (2011) stated in their study about experts' and novices' explanations of evolution, students with more complex explanations can have a high coherence among different contexts. Although this pattern can be observed in case 2 (see explanation in animal context-T4 and human context-T5), our findings show little coherence between the different

contexts, which can appear even with simple explanations, as in case 1 (T5, explanation composed by only M in all contexts). However, as previous studies have suggested (Chi, Kristensen, and Roscoe 2012; To, Tenenbaum, and Hogh 2017; Nehm 2018), it is likely that scientific explanations require certain scaffolds to be constructed. In this study, there seems to be a pattern that shows that the best explanations are based on necessity, while those students who claim not to know how evolution occurs at the beginning, tend to construct erroneous explanations alongside very few key concepts (see next section). As Chi, Kristensen, and Roscoe (2012) suggest, to understand natural selection students must develop an Emergent Causal Schema (scientific explanation) from a Direct Causal Schema (intuitive or naïve explanation) and not from nothing. Nevertheless, the step from an intuitive explanation to a complex one can be mediated by the correct understanding of the ontological level of natural selection. It is probable that students, in a first stage, understand natural selection as a state associated with the individual rather than as a process (Chi, Kristensen, and Roscoe 2012). This sequence or learning progression is like the developmental trend in students' emerging understandings about evolution proposed by To, Tenenbaum, and Hogh (2017), where the older are better able than the younger to incorporate scientific concepts in their explanations, probably the former had more instruction and progression through the National Curriculum. In the same vein, the developmental learning progression of Evans et al. (2012) also proposes that, when purposeful thinking is reframed as a naturalistic goal, it provides a crucial stepping-stone, paving the way to natural selection (Nehm 2018; Kampourakis 2020).

### *Learning trajectories of evolution on a conceptual landscape*

Along with the composition-structure-coherence framework used in this study to analyse individual trajectories, we also followed a procedure like the one outlined in Zabel and Gropengiesser (2011), with an enlightening change. Whereas Zabel and Gropengiesser (2011) used five conceptual frontiers to describe the learning trajectories of students, in our study we combine the idea of conceptual landscapes with the most used nomenclature to describe the learning progression proposed in the literature on understanding the mechanism of natural selection (Chi, Kristensen, and Roscoe 2012; Evans et al. 2012; Nehm 2018). In addition, in this work the learning trajectories of the students were explored in three different contexts: animal, plant and human evolution. Taking these modifications into account, our results coincide with the findings of Zabel and Gropengiesser (2011), who show that a large proportion of the students are climbing a ladder from description to intention to variation of type. In the current study, students that start in the 'do not know' layer, only manage to create an explanation of intention or a mixture of it with key concepts, while those students who start from an alternative conception such as teleology or Lamarckism have a better chance of arriving at a Darwinian explanation or an Emergent Causal Schema (Chi, Kristensen, and Roscoe 2012). However, it is also true that some students' thinking development roams in a conceptual landscape where different trajectories lead to the same goal (Zabel and Gropengiesser 2011) or the same student has different trajectories in different contexts.

## Conclusions, limitations, and further work

Despite some limitations in the study, such as the low number of students participating or the low number of lessons delivered, the purpose of the study, to describe and understand the change in students' thinking about evolution considering its' composition, structure, and coherence, was achieved. According to this, it can be said that the students who participated in this study show different trajectories, which are idiosyncratic and context-dependent; however, some patterns predicted by the theory accumulated up to this moment are also recognised (Zabel and Gropengiesser 2011; Chi, Kristensen, and Roscoe 2012; Nehm 2018). Some patterns are: the recurrence of the design teleology thinking in students, the initial use of key concepts such as mutation, survival and differential reproduction during the trajectories, the abundance of mixed thinking during and at

the end of the instruction, the low coherence in the structure of explanations, both in time and through the different contexts analysed, and the greater frequency of a learning sequence that goes from the absence of explanations, through intentionality and ending with explanations more focused on natural selection. All these conclusions must be considered with caution since our study included a low number of students, and the efficiency of instruction was lower than previously described in similar contexts (Cofré et al. 2018a). However, we believe that the greatest contribution of this study is the intention of synthesising both theoretical and methodological proposals that until now have been scattered in the literature on understanding and learning evolution by natural selection.

Future research should increase the number of students participating in the study, and a longer sequence of lessons could be implemented. On the other hand, a more in depth approach could include the analysis of conversations with individual students about their understanding of evolution. It might reveal another release of interconnected cognitive steps. Furthermore, another direction to go in might be a more in depth study of the relationship between instructional strategy implemented in lessons such as scientific argumentation, inquiry, or nature of science (Harms and Reiss 2019) and the learning progression in students' evolutionary thinking that is described in this research. For example, a pending question is whether the improvement in the thinking about evolution that the students makeis connected to their argumentation skills.

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## ORCID

Dirk Krüger http://orcid.org/0000-0003-0999-4382
Hernán Cofré http://orcid.org/0000-0003-2789-334X

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