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Conceptions of Portuguese Prospective Teachers about Real-Life Evolution Situations

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The importance of introducing evolution in primary schools has been highlighted in evolution education research, but few studies have approached the understanding of evolution of prospective teachers who are being prepared to teach at primary school level. The present exploratory study aims to answer three research questions about the ability of Portuguese prospective teachers to apply evolution to two real-life situations: 1) Are prospective teachers able to identify evolution misconceptions in online newspaper articles? 2) What misconceptions are expressed by prospective teachers when explaining real-life evolution situations? and 3) Which key evolution concepts do prospective teachers apply to make sense of real-life evolution situations? Twelve prospective teachers participated in the study. In the first situation, the prospective teachers were asked to identify statements from a newspaper article that would reveal evolution misconceptions and justify their choices. In the second situation, they were asked to read a text about SARS-CoV-2 and explain why scientists were worried about uncontrolled outbreaks of the virus. The prospective teachers' answers were analysed through content analysis. Regarding the first research question, our results show that only half of the prospective teachers were able to identify teleological misconceptions in the newspaper article. Concerning the second research question, some of the prospective teachers either identified misconceptions in information in which there was no misconception, or revealed their own misconceptions in their explanations. Regarding the third research question, although more than half of the prospective teachers identified at least two key evolution concepts, some of them found it difficult to explain how evolution is related to the situation described. Although this is an exploratory study, it shows which key concepts of evolution the prospective teachers mobilised and identifies their misunderstandings, thus highlighting dimensions that should be addressed in their evolution education.

Keywords: evolution, evolution education, evolution key concepts, evolution misconceptions, prospective teachers

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Predstave portugalskih bodočih učiteljev glede resničnih razmer evolucije

Bento Cavadas in Xana Sá-Pinto

Smisel uvajanja evolucije v osnovne šole je bil poudarjen v raziskavah evolucijskega izobraževanja, toda zelo malo študij se je približalo razumevanju evolucije, ki ga imajo bodoči učitelji med usposabljanjem za osnovnošolsko poučevanje. Namen te eksplorativne študije je odgovoriti na tri raziskovalna vprašanja o sposobnosti portugalskih bodočih učiteljev, da uporabijo znanje evolucije v dveh situacijah resničnega življenja: 1) Ali so bodoči učitelji sposobni prepoznati napačne predstave o evoluciji v poljudnih člankih na spletu? 2) Katere napačne predstave izražajo bodoči učitelji, ko razlagajo evolucijske situacije v resničnem življenju? 3) Katere ključne evolucijske koncepte uporabljajo bodoči učitelji, da bi osmislili resnične evolucijske situacije? V raziskavi je sodelovalo 12 bodočih učiteljev. V prvi situaciji so bili pozvani, da naj v časopisnem prispevku prepoznajo izjave, ki bi razkrile napačne predstave o evoluciji, in utemeljijo svoje odgovore. V drugi situaciji so morali prebrati besedilo o SARS-CoV-2 in pojasniti, zakaj so znanstveniki zaskrbljeni zaradi nenadzorovanih izbruhov virusa. Odgovore bodočih učiteljev smo analizirali z vsebinsko analizo. Glede na prvo raziskovalno vprašanje naši izsledki kažejo, da je le polovica bodočih učiteljev znala prepoznati teleološke napačne predstave v časopisnem prispevku. Pri drugem raziskovalnem vprašanju pa so nekateri bodoči učitelji ugotovili napačne predstave v informacijah, v katerih napačnih predstav sploh ni bilo, ali pa so v svojih razlagah razkrili lastne napačne predstave. Glede tretjega raziskovalnega vprašanja, čeprav je več kot polovica bodočih učiteljev identificirala vsaj dva ključna koncepta evolucije, so nekateri težko razložili, kako je evolucija povezana z opisano situacijo. Čeprav gre za eksplorativno študijo, ta vseeno prikazuje, na katere ključne koncepte evolucije so se bodoči učitelji sklicevali, obenem pa prav tako odkriva njihova nerazumevanja, s čimer osvetljuje dimenzije, ki bi jih bilo treba obravnavati v njihovem evolucijskem izobraževanju.

Ključne besede: evolucija, evolucijsko izobraževanje, ključni koncepti evolucije, napačne predstave o evoluciji, bodoči učitelji

Introduction

Many contemporary sustainability problems are related to species that evolve too slowly or too fast for humans to find solutions (Carrol et al., 2014). In the first group are species that evolve too slowly to cope with the pace of human and natural environmental changes. Some of these species are now facing extinction. The second group includes pathogens and many pest species that threaten human survival and/or well-being (Carrol et al., 2014), as shown by the recent global pandemic of coronavirus SARS-CoV-2. Understanding how viruses evolve, how new variants emerge, spread and become dominant, and how resistance to vaccines may evolve is relevant to increasing public understanding of and support for the policy measures taken in many countries.

Public understanding of evolution is thus fundamental to developing long-term solutions for these sustainability problems as well as public support for their implementation. This is one of the factors that have led several institutions and researchers to argue that evolution should be introduced from the first years of mandatory education (NRC, 2012). In fact, research (e.g., Naldelson, 2009) suggests that teaching evolution concepts to early primary school students can contribute to changing the levels of understanding and acceptance of the theory of evolution (Brown et al., 2022; Sá-Pinto et al., 2023; Sá-Pinto et al., 2021). However, this requires primary school teachers who are able to teach this subject.

In order to increase quality in evolution education, Tekkaya et al. (2012) argue that teachers should possess accurate conceptions and be adequately prepared to teach evolution with confidence. When teachers lack pedagogical content knowledge and believe they do not understand evolution, as well as other curriculum topics, that could undermine the confidence they need to be effective in teaching evolution (Tekkaya et al., 2012). Therefore, to prepare them to teach evolution, Sickel and Friedrichsen (2013) suggest that teachers should develop content knowledge on evolution, understand the nature of science related to evolution, increase their acceptance of evolution and their willingness to teach the topic, and develop their knowledge on strategies for handling controversy and their pedagogical content knowledge for teaching evolution. These goals accord with the conclusion of the study by Tekkaya et al. (2012), which shows that teachers' acceptance of the scientific validity of evolution and their perceptions about the importance of addressing evolution in their classes is related to a good understanding of evolution and the nature of science. Following this line of reasoning, Tekkaya et al. (2012) suggest that it is important to adequately design teacher education programmes to enhance teachers' understanding of evolution and the nature of science.

Preparing prospective teachers (PTs) to teach evolution is a multifaceted task. Nadelson (2009) noticed that, after exploring in-depth tutorials, preservice teachers integrate the nature of science and biological evolution concepts more often than the relationship between uncertainty and evolution in their lesson ideas for teaching evolution. However, some preservice teachers maintained misconceptions about evolution and the nature of science. This is a problem because there is potential for these views to be taught to young students by their teachers (Fisher, 2004). Nadelson (2009) also noticed that some American preservice teachers showed reduced acceptance of evolution and, in their lesson ideas, proposed teaching creationism as an equally acceptable explanation for the origin of species. This vision is also shared by some Portuguese preservice teachers (Cavadas & Sá-Pinto, 2021), which could be partially explained by the lack of preservice teachers' understanding of the meaning of scientific theories (Nadelson, 2009).

Several authors argue for the importance of introducing evolution in primary schools, but few have studied the understanding of evolution of preservice teachers who are being prepared to teach at that level. Research suggests that primary teachers are not well positioned to teach evolution (Herman, 2018; Prinou et al., 2011). Hermann (2018) found that the willingness of preservice primary teachers to specialise in science increases as their acceptance of evolution rises, and vice versa. Furthermore, Hermann (2018) noticed that the willingness of prospective primary teachers to specialise in science increased, although not significantly, with their understanding of natural selection. The implication of Hermann's (2018) study is that the preservice teachers who could serve as science specialists in primary schools are those who have both a willingness to specialise in science and a higher acceptance of evolution. Within their functions as science specialists, prospective primary teachers could develop curricula, create educational resources and work with their peers in effective science learning experiments for primary school children (Hermann, 2018). Therefore, more studies that research future teachers' understanding of evolution are needed.

Evolution misconceptions

Having misconceptions related to evolution may hinder the ability to learn new concepts and develop effective science-based solutions for diversified sustainability problems (Jørgensen et al., 2019; Nadelson, 2009). In a study involving 9,200 participants, Kuschmierz et al. (2021) found that European first-year university students mostly accept evolution but lack substantial knowledge about it. Furthermore, they found that country affiliation and education system play only a minimal role in the acceptance of evolution. Even among students enrolled in biology-related programmes, the level of knowledge varies greatly, and religious faith was a better predictor of students' acceptance of evolution than their knowledge about evolution (Kuschmierz et al., 2021).

Some important misconceptions about evolution are related to teleological thinking. Wagner-Egger et al. (2018) defined teleological thinking as the attribution of purpose and a final cause to natural events and entities. Many studies report a high frequency of misconceptions related to teleological thinking in young adults, which are persistent and difficult to change, even using educational programmes specifically designed to address them (Bishop & Anderson, 1986; Nehm & Reilly, 2007). Some researchers have proposed that teleological thinking is innate or developed in early childhood (reviewed in Kelemen, 1999a). Young children apply teleological thinking indiscriminately to both biological and non-biological agents, while adults seem to selectively apply it to human-made artefacts and biological agents (Kelemen, 1999b). Kelemen (1999b) also showed that a very large proportion of adults still provide teleological explanations to biological parts of living organisms and even to biological entities (e.g., babies or plants).

Several studies have suggested that teleological thinking in evolution can be reinforced throughout a person's life by teachers, books, the media and even by the way evolutionary biologists speak about evolution (Nehm et al., 2010; Prinou et al., 2011). This hypothesis is supported by recent findings that show that primary school students provide few teleological explanations (Sá Pinto et al., 2021) and that they can easily overcome these with instruction (Brown et al., 2020). Together, these results support the importance of the early introduction of evolution in students' education. However, Prinou et al. (2011) showed that primary school teachers hold evolution misconceptions themselves, further supporting the importance of providing PTs with training on evolution and on evolution misconceptions. Prinou et al. (2011) also noted that, in Greek primary education textbooks, the concept of 'adaptation' is presented through misleading teleological explanations, highlighting the fact that teleological explanations are used by schools to explain the origin of the features in organisms. In fact, only a small percentage of the primary education teachers who participated in the Prinou et al. (2011) study interpreted the origin of adaptation in a scientific way, mixing their answers with ideas that have teleological connotations.

Evolution key concepts

In order to fully understand evolution by natural selection and use this knowledge to grasp biological systems and address problems caused by biological agents, students need to understand, articulate and put into action several concepts. Different authors have proposed distinct lists of concepts that, according to them, are fundamental to understanding evolution by natural selection (Anderson et al., 2002; Nehm & Ridgway, 2011; Tibell & Harms, 2017). Recently, Tibell and Harms (2017) reviewed previous works and proposed a list of principles, key concepts and threshold concepts that they believe are fundamental to understanding natural selection. Key concepts are purely biological concepts, which Tibell and Harms (2017) organised into three main principles: variation (which includes the key concepts of mutations as the cause for variation, phenotypic variation and differential fitness), heredity (which includes the key concept of traits that are heritable through reproduction) and selection (which includes the key concepts of selective pressure, differential survival, differential reproduction, changes in populations and speciation). According to the same authors, threshold concepts are concepts that, when acquired, are transformative and open new possibilities for students to develop their knowledge, thus facilitating conceptual change. Tibell and Harms (2017) propose that randomness, probability, spatial scales and temporal scales are the threshold concepts that facilitate the learning of evolution, and claim that key concepts and threshold concepts should always be considered when teaching about evolution. They also suggest that these concepts may be combined to facilitate students' learning processes and promote a deeper understanding of evolution and its implications in and applications to daily life situations. However, teachers' themselves need to be empowered with knowledge and skills about these concepts in order to better teach evolution.

Aim and research questions

Kuschmierz et al. (2020) point out that a comprehensive overview of the state of knowledge about evolution and acceptance of evolution in different educational settings is needed. The present study aims to make a small contribution to that overview, presenting data about Portuguese PTs' knowledge of evolution. The aim of the present study was to explore PTs' performance in applying evolution to real-life situations. The research questions (RQ) that guided this study are:

1. Are PTs able to identify evolution misconceptions in newspaper articles?

2. What misconceptions are expressed by PTs when explaining real-life evolution situations?
3. Which principles, key concepts and threshold concepts for understanding natural selection do PTs apply to make sense of the real-life evolution situations presented?«

Method

Research design and data collection

The participants were 12 senior PTs of a three-year initial teacher education programme from a Portuguese higher education institution. In this programme, PTs attend general education subjects, as well as specific content knowledge subjects, such as Portuguese, arts, mathematics, science, history and geography. The programme also includes an introduction to the didactics of these subjects as well as short internships.

The present study was implemented when the PTs were coursing the subject of Earth and Life Sciences in the final semester of their programme. A number from 1 to 12 was used to identify each PT (e.g., PT1, PT2). All of the participants were informed about the context of the study and provided their informed consent to data collection, analysis and publication.

Two problems related to real-life evolution situations using online newspaper articles were presented to the PTs (Table 1).

Table 1
Real-life evolution situations and problems proposed

Situation 1 Plant evolution problem	The PTs had to identify evolution misconceptions in a news article published online about the plant *Fritillaria delavayi*, the headline of which is »Meet the Chinese plant that changes colour because it is afraid of man« (Tempo.pt, 2020). The article presents the common misconception that natural selection implies that organisms try to adapt to a certain situation to survive. Specifically, the text suggests that the plant changed its colour to better camouflage itself in the environment, thus avoiding being picked by humans.
Situation 2 SARS-CoV-2 evolution problem	The PTs had to read a news article about a real-life evolution situation concerning the SARS-CoV-2 virus (Otto, 2021). The article presented the researchers' concern about the new variants of the virus and the areas where virus infections were not controlled.

Situation 1 was chosen because it is a news article that describes a macro-organism – a plant – that, according to the text, had intentionally evolved to cope with human harvesting. Situation 2 was chosen because it is related to acellular microorganism evolution, namely SARS-CoV-2, which is a relevant context for understanding evolution. Situation 2 was presented to the PTs during the pandemic, so increased interest for this situation by the PTs was expected. Other authors, such as Hsu (2020), have used data related to the evolution and transmission of SARS-CoV-2 as a context to promote students' discussion and learning of evolutionary principles.

In the first situation, the PTs were asked to identify the misconceptions about evolution in the article and to justify their answer. In the second situation, they were asked to explain, in the light of evolution principles, why it is dangerous to allow the uncontrolled reproduction of the virus.

The PTs received a form that included the two newspaper articles, their respective problems and a blank space for them to write their answers. Both of the situations were proposed to the PTs by the teacher of Earth and Life Sciences in an in-person class. They had a week to individually search for information related to these situations in order to support their answers to the problems presented. They had to present the references of the books, papers or online pages they used to create the answers. Each answer was limited to maximum of 300 words, excluding references. The PTs wrote their answers on a form and submitted it on a learning management system platform (Moodle). All of the PTs submitted their answers within the determined timeframe.

Data analysis

The PTs' answers were subjected to content analysis. RQ1 was mostly answered based on the PTs' outputs to Situation 1. To this end, the two authors of the paper identified the statements in the text that expressed misconceptions. Five statements with clear misconceptions were identified in the main text of the news article: Statement 1 – »Meet the Chinese plant that changes colour because it is afraid of man«; Statement 2 – »A plant used in traditional Chinese medicine may have evolved to become less visible to humans«; Statement 3 – »Over time, it evolved to go unnoticed in our eyes, transforming its striking greenish colour into a withered brown that blends with the soil«; Statement 4 – »The fear of man had made plants change colour in an ingenious strategy to survive«; Statement 5 – »Many plants use the cloaking mechanism to hide from the herbivores that can eat them, but in this case camouflage has evolved as a response to human collectors«. The authors analysed the PTs' answers and registered which statements they correctly identified as expressing misconceptions. As the PTs were asked to identify misconceptions and not to identify all of the statements that expressed a misconception, in the final results the authors counted the number of PTs who correctly identified at least one of the respective misconceptions.

RQ2 was answered by analysing both situations. For Situation 1, in order to answer RQ2 the authors: i) identified the statements that the PTs incorrectly classified as misconceptions; ii) analysed the justifications provided by the PTs and identified misconceptions they expressed, classifying them into categories based on the ideas presented by the PTs, which is a procedure also used by other researchers (e.g., Merriam, 2009). The latter procedure was also used to identify the misconceptions expressed by the PTs in Situation 2.

In order to answer RQ3, the authors designed and applied a system of categories of analysis based on the principles, key concepts and threshold concepts of evolution by natural selection proposed by Tibell and Harms (2017). Three categories were created for the principles of evolution, one for each of the three principles described by the authors (variation, heredity and selection). To further refine the analysis, subcategories within each category were created, reflecting the key concepts for each principle suggested by Tibell and Harms (2017; see the categories of analysis in Table 1). Two of the key concepts mentioned by the authors – differential fitness and frequency change through time – were excluded from the analysis of Situation 1. Differential fitness was omitted from the analysis because this key concept is based on the concepts of differential survival and differential reproduction, which are two of the subcategories of the selection principle. Frequency change through generations was also excluded from the analysis of Situation 1 because this key concept was explicitly described in the newspaper article provided to the PTs. Finally, speciation was not included either, as we were mostly interested in the microevolutionary process taking place at the population levels. For Situation 2, the key concepts of differential survival and differential reproduction were excluded because they are difficult to observe, distinguish and explain for a virus infecting hosts. As a proxy for these concepts, we used the key concept of differential fitness, which results from a combination of survival and reproduction. To identify differential fitness, evidence of the PTs mentioning variations in terms of replicative fitness, transmission fitness and epidemiological fitness was searched (following Wargo & Kurath, 2012). Following Tibell and Harms (2017), four categories were created for the threshold concepts: randomness, probability, temporal scale and spatial scale. For each category, the analysis was refined using subcategories based on the evidence that we would expect to find in a complete and correct answer to the question that would fit each of the four categories (see the categories of analysis in Table 1). For Situation 1, the threshold concepts were not analysed in the PTs' answers because the task submitted to them was more focused on their ability to detect misconceptions.

At the beginning of the coding process, both of the authors read all of the PTs' answers and collaboratively: i) defined the categories of analysis relative to RQ1 and RQ2; and ii) redefined the categories of analysis for RQ3. After this initial step, one of the authors coded all of the PTs' answers by looking for the presence or absence of evidence supporting each category. When a PT's answer could not be clearly classified as belonging to a given category, the PT was not counted in the analysis of this category. This is why the PT count in Table 1 and Table 2 is not equal to the sample size of 12 in some categories. To analyse the reliability of the analysis, 25% of the PTs' answers were independently read and coded by the other author. Given the evaluators' training, interrater reliability was estimated as the percentage of initial agreement between the evaluators (McHugh, 2012). Interrater reliability was higher than 70%, the threshold for the reliability to be considered as acceptable according to Stemler (2004).

Results

Situation 1 | Plant evolution problem

RQ1) Misconceptions identified by the prospective teachers

The results from Situation 1 (Table 1) revealed that 8 of the PTs (67%) were able to correctly identify statements with teleological misconceptions in the text. To justify their choices, half of the PTs stated that evolution does not have a purpose, nor does it depend on the individuals' needs, as exemplified by the following statement: »The first misconception that the article presents is that the plant has evolved over time to go unnoticed by our eyes« (PT11).

RQ2) Misconceptions revealed by the prospective teachers

Of the 12 PTs, 64% either: a) identified as misconceptions information that was not related to a misconception, or b) revealed their own misconceptions in their explanations (Table 1). The most frequent misconception in the text was that humans were not able to cause the species' evolution. The PTs who revealed this misconception most often state that humans were not the cause of the mutation giving rise to the brown phenotype, failing to identify that the humans were the cause for the selective pressure (plant collection) that caused the frequency change. An example of this misconception is expressed by PT2, who seems to believe that humans can cause the extinction of genes, but cannot act as selective pressure on genes: »Therefore, evolution does not occur, but the extinction of a certain genetic code. In this case, the human being is not the cause of evolution, but the cause of extinction. To be the cause of evolution, as the article claims, it would have to interfere directly with the DNA of plants«. However, the online newspaper article clearly states that the level of camouflage in that plant species was related to human harvesting pressure. It also states that the most camouflaged specimens took longer to be detected and were more frequent in places with higher harvesting pressure, including a citation from the researcher conducting the study stating that »commercial harvesting is a selective pressure stronger than many others in nature«.

Another misconception expressed by the students was that evolution is only a slow process. An example of this is the following reasoning of PT1: »Also in the same paragraph of the article it is mentioned that it is possible that the plant evolved in a short period of time. Now, according to the theories of evolution, these major transformations of species occur gradually and over a long period of time«. Other stated misconceptions included teleological explanations and ideas that expressed the inheritance of acquired features.

RQ3) Principles and key concepts of evolution mobilised by the prospective teachers

Ten of the PTs tried to explain the evolutionary process presented in Situation 1 by the means of natural selection. Of these, three were able to correctly mention and connect five of the six key concepts, and only two mentioned all six key concepts. Heredity was commonly approached, and some PTs expressed ideas about that process, e.g., PT2: »the genetic code is transmitted between generations, through the process of heredity«. However, the PTs did not clearly mention reproduction in their reasoning about the process that causes the transmission of the genetic code between generations.

The least mentioned key concepts were 'mutations are the cause of variation' and 'differential reproduction'. Differential survival and differential reproduction are clearly mentioned, for example, by PT2: »If humans are harvesting plants with a certain genetic code *en masse*, the ones that survive will be those that have a chance to reproduce and consequently generate new plants with their DNA« (PT2).

Situation 2 | SARS-CoV-2 evolution problem

RQ2) Misconceptions revealed by the prospective teachers

Teleological misconceptions about the evolution of SARS-CoV-2 were presented by the PTs. One example of such a misconception is evident in the following statement: »The characteristics of SARS-CoV-2, which is being refined through its many genetic variants« (PT1). Another PT reported about the

HIV virus and presented teleological conceptions: »In short, we cannot let the virus reproduce uncontrollably because we have HIV in our society, which has modified its genetics to become immune« (PT12).

When asked to explain, in the light of evolution, why it is dangerous to allow uncontrolled reproduction of the virus, the PTs applied several evolution key and threshold concepts.

RQ3) Principles and key concepts of evolution mobilised by the prospective teachers

Regarding the key concepts, all or almost all of the PTs identified the existence of intraspecific variation and stated that this variation was due to mutations (one PT also mentioned recombination as a source of diversity). One PT related the new variants to higher risks of transmission: »These (variants) have a genome that is distinct from the original genetic code and presents a much higher risk of transmissibility, as well as the possibility of causing more serious damage in certain organisms« (PT5). None of the PTs mentioned that the mutations that occur in a particular virus would be transmitted to its descendants. In fact, the notion that traits are passed from one virus to another through reproduction was only expressed by one PT: »when they (viruses) enter the cells they exploit the cellular machinery by making copies of themselves over and over again« (PT2). Moreover, although seven of the PTs identified vaccines, the immunological system or drugs as factors imposing selective pressures that could differently impact the ability to reproduce, the transmissibility or epidemiological behaviour of the diverse SARS-CoV-2 variants, they mostly expressed this idea by mentioning that new variants of the virus could reduce the protection conferred to humans by those factors. They did not further elaborate on this idea to describe how this would differently impact the frequency of the strains across time and space. Seven of the PTs mentioned the existence of differential fitness between distinct variants, while five mentioned that this would lead to variants' frequency change through time and/or space. However, the differential fitness processes mentioned by most of the PTs are caused by the increased ability to infect or be transmitted between humans, and are not directly linked to vaccines, immunological system or drug resistance. One PT described the process of natural selection, but taking place in humans, stating that individuals who were not resistant to SARS-CoV-2 had increased mortality.

Regarding the threshold concepts, more than half of the PTs applied the concept of randomness to the mutations, as exemplified by this statement: »these copies (of the virus) can mutate, due to random errors during protein synthesis, generating variants with new properties« (PT2). Six of the PTs applied the concept of probability to describe the low probability of an adaptive mutation happening (2), or to explain that the higher the population size, the higher the possibility of having an adaptive mutation (4). This was the case of PT7, who stated: »The more the virus replicates, the more mutations will occur. New variants will emerge and within them there will be a greater probability of being more infectious, since there are more variants.«

A high proportion of the PTs (90%) were able to apply more than one spatial scale in their answers, typically mentioning the mutations taking place in virus RNA within our cell and impacting the pandemic at a global level. Fewer of the PTs specifically mentioned changes in the variants' frequencies through space (7) and time (4). One exception is PT11, as exemplified in the following statement: »It is dangerous to allow the SARS-CoV-2 virus to reproduce uncontrollably because new variants of it emerge, as has already happened with variants in South Africa, the UK and Brazil!». None of the PTs mentioned genetic drift as a cause of variants' frequency changes. Three of the PTs revealed teleological misconceptions in their explanation.

Table 1

Results obtained for Situation 1: Frequency of prospective teachers who identified or expressed a misconception and applied the evolution principles and key concepts to answer the problem about plant evolution

	Misconceptions identified	Misconceptions expressed				Principles and key concepts of evolution					
						Variation		Heredity	Selection		
Prospective teachers	Identification of at least one teleological idea	Humans do not affect plant evolution (evolution = mutation)	Teleological	Inheritance of acquired features	Evolution cannot be a fast process	Mutations are the cause of variation	There is individual phenotypic variation	Some traits are heritable and passed from parents to offspring	Selective pressure	Differential survival	Differential reproduction
Absolute frequency	8	5	1	3	2	2	10	8	8	8	6
n	12	12	12	11	12	10	10	10	10	10	10
Relative frequency	0.67	0.42	0.08	0.27	0.17	0.20	1	0.80	0.80	0.80	0.60

Note. n – total number of PTs' answers coded for each criterion without doubts.

Table 2

Results obtained for Situation 2: Frequency of prospective teachers expressing misconceptions, applying principles, key concepts and threshold concepts to answer the problem about SARS-CoV-2 *evolution*

	Misconceptions expressed	Principles and key concepts of evolution						Threshold concepts of evolution						
		Variation		Heredity	Selection			Randomness		Probability		Temporal scale	Spatial scale	
Prospective teachers	Teleological	Mutations are the cause of variation	There is individual phenotypic variation	Heritable traits are passed from parents to offspring	Selective pressure	Differential fitness	Changes in population	Mutations are random	Genetic drift	The probability of a mutation being fitter is low	The higher the population size the higher the probability	Frequency change through time	Frequency change through space	More than one spatial scale is mentioned
Absolute frequency	3	10	12	0	7	7	5	7	0	2	4	3	7	11
n	12	11	12	12	12	12	12	12	12	12	12	12	12	12
Relative frequency	0.25	0.91	1	0	0.58	0.58	0.42	0.58	0	0.17	0.33	0.25	0.58	0.92

Note. n – total number of PTs' answers coded for each criterion without doubts.

Discussion and implications for the evolution education of prospective teachers

This section presents a discussion of the results of the PTs' answers about the problems of both of the real-life evolution situations and their implications for their evolution education.

RQ1) Misconceptions identified by the PTs in Situation 1

Most of the PTs who participated in the present study revealed an awareness of teleological misconceptions regarding evolution. In Situation 1, most of the PTs perceived that the plant, *Fritillaria delavayi*, did not evolve to achieve a purpose. However, a significant proportion of the PTs (33%) failed to identify the misconceptions present in the text. These results are in line with those of Fischer et al. (2021), who showed that PTs find it hard to identify teleological misconceptions. This suggests that further training is needed to empower PTs to identify evolution misconceptions. Such training could also lead them to prepare better interventions to support their own students in overcoming their misconceptions when addressing evolution situations, as suggested by Brown et al. (2020).

RQ2) Misconceptions expressed by the PTs in Situations 1 and 2

Although most of the PTs were able to identify misconceptions, some of them also expressed misconceptions when justifying their reasoning. For example, some of the PTs expressed the misconception that humans do not affect, or have a small influence on, plant evolution in Situation 1. PT1 illustrates this point clearly: »It is also unlikely that the camouflage of *Fritillaria delavayi* is directly due to the human action of harvesting«. This reveals the importance of PTs' evolution education to clarify that humans can directly impact the strength and direction of selection, either intentionally or inadvertently. Moreover, it should be clarified that this process is led by the selective pressure imposed by humans as they cause differential survival and reproduction in a population, and not by evolutionary 'needs' or 'purposes' of the target species. Some of the PTs who mentioned that humans could not drive evolution revealed an additional misconception, as they seem to think that evolution is only the initial mutation. They failed to understand evolution as the gene frequency change through time, and that the human harvesting was the selective pressure driving such change. It is thus fundamental to clarify that evolution is the process of frequency change through time, and that this process requires diversity (originated initially by mutation) in heritable characters (Tibell & Harms, 2017).

Research shows that students tend to apply different normative ideas and misconceptions to similar evolutionary problems if these differ in superficial features (e.g., if one problem involves a plant and the other an animal; Nehm & Ridgway, 2011; reviewed in Nehm, 2018). This is explained by the fact that the different surface features of the problems result in the activation of distinct concepts and problem-solving schemas that lead to different approaches and explanations being provided by the students. This may explain the higher number of PTs expressing teleological ideas to reason about the evolution of viruses, as viruses have very different biological properties from the species usually used to teach evolution. Our results thus support the thesis that the evolution of viruses should be addressed in PTs' education, given its very different biological properties.

Although only three of the PTs presented the idea of inheritance of acquired features, resembling Lamarckian explanations, this alerted the authors of this paper to the fact that the topic 'history of science' should be reinforced in the evolution education of PTs, who should be taught why the Lamarckian evolution ideas proposed in the nineteenth century are not accepted nowadays.

Another misconception identified in two of the PTs is that evolution is a very slow process. One model of macroevolution, called phyletic gradualism, proposes that »most speciation events are the result of a gradual and uniform transformation of one species into a new one through a process called anagenesis« (Sesink Clee & Gonder, 2012). In this model of macroevolution, the key element is vast amounts of time (Sesink Clee & Gonder, 2012). The need for vast amounts of time for macroevolution to occur could have influenced the reasoning of the PTs in the present study. Furthermore, this idea could result from an unclear conceptualisation of microevolution, which describes mechanisms that alter the frequencies of alleles in gene pools within species (Reznick & Ricklefs, 2009). These mechanisms include mutation, migration, genetic drift and natural selection (Sesink Clee & Gonder, 2012). For PT1, for example, the colour change of a plant was due to a major phenotypic transformation and was not perceived as the change in the frequencies of alleles in the population, which can be a fast process. Microevolution can be observed over a short period of time, such as across a few generations (Choudhuri, 2014). Although only two of the PTs considered that evolution is always a very slow process, we suggest that, for a proper understanding of evolution, the distinction between macroevolution and microevolution, as well as the features of these processes, should be addressed in PTs' evolution education.

RQ3) Principles, key concepts and threshold concepts of evolution mobilised by the PTs about Situations 1 and 2

Principles and key concepts of natural selection

Some relevant differences were found in the frequency of the PTs' applying the principles and key concepts to explain Situations 1 and 2. This can be explained by the differences between the two questions (the type of task submitted to the PTs, the material provided for them to read about the situation, etc.). However, given the different organisms and biological scenarios used to explore evolutionary processes, the different concepts used could also be due to the distinct concepts and problem-solving schemes that these activate in PTs (Nehm & Ridgway, 2011; reviewed in Nehm, 2018). The PTs' previous knowledge of the biology of plants and viruses may have influenced the concepts used in each situation.

While variation and selection principles of natural selection were mobilised by the PTs to answer both Situation 1 and 2, heredity was only mobilised to explain Situation 1. The idea that heritable traits are passed from parents to offspring (Tibell & Harms, 2017) was commonly used by the PTs in Situation 1, but only one PT applied it properly to Situation 2. The difficulty of understanding the cellular process of virus reproduction could be one of the reasons behind the reduced mobilisation of this concept by the PTs when addressing Situation

2. Another possibility is that the PTs used 'propagation' (PT11) to refer not only to virus dissemination in human populations, but also to consider virus reproduction. These results suggest that it is important to explore the specificities of viruses' reproduction in PTs' evolution education.

Regarding the key concepts applied, a great difference was found between Situations 1 and 2 concerning variation as a result of mutation. In the first situation, only two of the PTs mentioned this idea, which was used by the majority of PTs to make sense of the second situation. One reason for the observed difference is that the term 'mutation' is often used in the text of Situation 2 but is absent in Situation 1. The term mutation was also frequently employed by mainstream Portuguese newspapers to explain the emergence of SARS-CoV-2 variants (see two examples from two different newspapers in Serafim, 2020 and in Novais, 2021). Given that mass media played a very important role in the dissemination of SARS-CoV-2-related information (e.g., Corine et al., 2022; Dhanashree et al. 2021), the use of this concept by the Portuguese media when communicating about SARS-CoV-2 may also have contributed to its activation in the PTs when addressing this situation.

Regarding the principle of selection, many of the PTs identified human harvesting as the selective pressure that had caused the plant's evolution in Situation 1, while vaccines, the immunological system or drugs were identified as a selective pressure that differently affects the transmissibility or epidemiological behaviour of the SARS-CoV-2 variants in Situation 2. In Situation 1, it was noticed that the concept of differential survival was more often mobilised by PTs than that of differential reproduction, which is consistent with studies carried out with primary school students (e.g., Brown et al., 2020; Sá-Pinto et al., 2021). However, differential reproduction – a process by which some individuals leave more offspring in the next generation than others, often due to traits that confer advantages in survival and/or reproduction (UC Museum of Paleontology Understanding Evolution, s.d.) – is much closer to the concept of fitness and is in fact what drives evolution (reviewed in Sá-Pinto et al., 2017). It is thus important that PTs recognise the importance of this concept and are able to use it to make sense of and teach about situations of biological evolution.

Although some of the PTs mobilised differential fitness, the probabilistic nature of this process was not explicitly mentioned in their answers. Therefore, highlighting the probabilistic nature of differential reproduction, as well as differential survival and reproduction, as suggested by Tibell and Harms (2017), should be considered in PTs' evolution education.

In Situation 2, the key concept of change in population was addressed only by five PTs. The fact that SARS-CoV-2 has many variants, and that, over time, some variants prevailed replacing others (facts that were mentioned in the text that supports Situation 2) may have contributed to the mobilisation of this key concept. Furthermore, although the PTs identified vaccines, the immunological system or drugs as selective pressures, they did not connect this concept to the change in the populations. In fact, it seems that PTs did not understand the impact of the selective pressures on the frequency of the virus variants and on the consequent changes in the SARS-CoV-2 virus population. This knowledge fragmentation, expressed by the inability to link key concepts required to understand a process, can prevent PTs' deep understanding of situations involving evolutionary processes. According to Vergnaud (2009), this knowledge fragmentation pattern can be specific to the situation addressed and can only be overcome by exploring a variety of distinct situations that allow students to identify the set of a concept's invariants (objects, properties and relationships), thus allowing students to apply it to make sense of new situations and to solve new problems. This further supports the need to explore evolutionary processes under a variety of distinct contexts and model species.

Threshold concepts of evolution

The threshold concepts of evolution were unequally mobilised by the PTs in Situation 2. Randomness is defined as the »lack of pattern and predictability in events« (Tibell & Harms, 2017, p. 959). Seven of the PTs approached the random nature of virus mutations, which is good evidence of their understanding of the way this process leads to new ways of biological variation. However, none of them applied the concept of genetic drift to Situation 2, which could be an indicator of their lack of knowledge about this concept and the need to reinforce it in the evolution education of PTs.

Regarding probability, only four of the PTs presented this threshold concept in their reasoning about SARS-CoV-2 evolution. The idea that the larger the population size, the higher the number of mutations that take place (including adaptive mutations), was uncommon and should be properly addressed in the evolution education of PTs. This is particularly worrying, as failing to understand how population size affects biodiversity and the adaptive potential of the species (reviewed in Funk et al., 2019; Sato et al., 2020) may prevent people from understanding the importance of support measures taken in the management of diseases, pest species and endangered species.

As stated by Tibell and Harms (2017), understanding natural selection requires understanding multiple levels of organisation, such as the temporal and spatial scales of natural selection processes. In this exploratory study, the spatial scale threshold concept was mobilised more often by the participants than the temporal scale. This difference suggests that these threshold concepts should also be approached in the evolution education of PTs, with special attention to the temporal scale. It is also interesting to note that the PTs show clear evidence of being able to think over multiple spatial time scales (from the microscopic scale of virus reproduction to the global scale of the spread of new variants across countries and continents), an ability that is needed for systems thinking, one of the key competencies in sustainability (Wiek et al., 2011).

Suggestions for evolution education with prospective teachers

One idea that emerges from the analysis of the results is that PTs sometimes lack substantial knowledge about evolution key concepts, a result that supports the findings of Kuschmierz et al. (2021). Therefore, as a consequence of the above results and discussion, the following suggestions for evolution education with prospective teachers are presented.

In order to avoid evolution misconceptions, prospective teachers should understand that:

1. Evolution is not teleological, which means it has no direction or goal. Evolution does not have a purpose, nor does it tend to perfect organisms over time.
2. Human actions may become important selective pressures and can therefore influence evolution (e.g., the reduction of adult fish in nature due to fishing pressure (Kuparinen et al., 2016); the introduction of exotic species (Mooney & Cleland, 2001).
3. Evolution can, under some conditions, be a fast process.

In order to improve prospective teachers' understanding of evolution, the following should be stressed:

1. The meaning of microevolution and how it relates to macroevolution.
2. The meaning of adaptation.
3. Genetic variation is the primary cause of phenotypic variation.
4. Evolution is the change of gene frequency in populations over time.
5. Different situations and organisms should be used to explore evolution, including plants and viruses, to allow students to identify the key principles and concepts, and how these are linked, so as to apply them to a variety of situations.
6. The meaning of fitness, differential survival and differential reproduction, and how these key concepts are related and can be applied to make sense of adaptive processes.
7. Genetic drift, as an important process driving biological evolution.

8. The correlation of population sizes with the adaptive potential of a species.
9. Understanding evolutionary processes requires thinking at multiple levels of organisational, temporal and spatial scales.

Further research could study whether a better understanding of the principles and key concepts of evolution is related to a reduced or non-existent expression of misconceptions about evolution, specifically teleological conceptions. Another recommendation for research is focusing on students' ability to make sense of antimicrobial resistance and conservation problems from an evolutionary perspective, as these are important global sustainability problems that require long-term solutions informed by evolutionary biology.

Conclusion

The PTs who participated in the present study were able to identify misconceptions. Most of them identified teleological conceptions in Situation 1, showing their awareness that evolution is a natural process and not driven by a goal or cause.

However, misconceptions were also expressed by the PTs. For example, some teleological ideas arose concerning the intentional evolution of viruses to become more transmissive to humans, and attention should therefore also be paid to this aspect in the evolution education of PTs. Although the number of PTs who participated in the study was limited, from the misconceptions they expressed some insights emerged that could inform future evolution education of PTs, such as highlighting the idea that humans can impact evolution, exploring the notion that evolution is gene frequency change and that it can be a fast process, detailing the meaning of adaptation, and approaching the history of the science of evolution, with an emphasis on Lamarckism and why this explanation has not prevailed through time.

Concerning the key concepts of evolution mobilised, it was noted that individual phenotypic variation was an easier concept to grasp than genetic variation, and that differential survival was also easier to mobilise than differential reproduction. Differential fitness seemed to be easier to apply to viruses, rather than differential survival and reproduction. The threshold concepts of probability and temporal scale, especially when applied to viruses, also deserve further attention. Therefore, we suggest these concepts be reinforced in PTs' evolution education.

By addressing the above topics in the evolution education of PTs, their pedagogical content knowledge and confidence to teach evolution may increase, thus improving their performance when teaching this topic.

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