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ARTIGO ORIGINAL

Evolution as the cornerstone of biology: a course for undergraduates and postgraduates in biological sciences

Evolução como eixo central da biologia: um curso para graduandos e pós-graduandos em ciências biológicas

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Abstract: Although many authors share the view of evolution as the cornerstone of biological sciences, not many courses are effectively based off it. In this study, we have designed a course with this in mind, aimed at undergraduates and postgraduates in biological sciences. We intend to evaluate and compare the responses of both types of students using a survey questionnaire. Participants are undergraduate and graduate biology students from public and private universities in southern Brazil. We obtained 122 precourse and 95 post-course survey responses. Results suggest that students from all levels of biology training benefit from a teaching approach that takes evolutionary theory across biological disciplines. Pre- and post-course comparisons show that more training in biology does not equal more evolutionary knowledge. This may be one of the main advantages of a multidisciplinary approach to teaching evolution.

Keywords: Biology teaching; Evolution; Teacher training; Multidisciplinarity; Higher education.

Resumo: A importância da evolução como um eixo central da biologia é reconhecida por muitos autores. Este estudo descreve um curso voltado para esse fim, destinado à formação continuada de estudantes de biologia e professores. Pretendemos avaliar e comparar as respostas dos alunos antes e depois do curso através de um questionário de pesquisa desenvolvido e validado para as finalidades desta pesquisa. Os participantes são alunos de graduação e de pós-graduação em biologia de universidades públicas e privadas do sul do Brasil. Como nossos resultados indicam, os alunos de todos os níveis de formação em biologia se beneficiam de uma abordagem de ensino que trata a evolução como um eixo central do ensino de biologia. As comparações pré e pós-curso mostram que o nível de formação em biologia não indica um amplo conhecimento evolutivo e esta pode ser uma das principais vantagens de uma abordagem multidisciplinar no ensino da evolução.

Palavras-chave: Ensino de biologia; Evolução; Formação continuada de professores; Multidisciplinaridade; Ensino superior.

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Introduction

Evolution is a cornerstone of biology (ARAÚJO, 2020; HANISCH; EIRDOSH, 2020; HARMS; REISS, 2019; MAYR, 1961). Perhaps the best-known sentence to express this idea comes from Theodosius Dobzhansky's (DOBZHANSKY, 1973) famous essay Nothing in biology makes sense except in the light of evolution. Despite the power and influence of this theory, evolution is commonly taken as an ordinary topic biology curriculum in many countries around the world, even at higher levels of education (BIZZO; EL-HANI, 2009; HANISCH; EIRDOSH, 2020; PRICE; PEREZ, 2016; TAVARES; BOBROWSKI, 2018). Moreover, most science curricula tend to focus on natural selection and genetic aspects of microevolution (NADELSON; SOUTHERLAND, 2009; PADIAN, 2010). Evolution generally refers to changes in populations due to the generation of variation and natural selection, so that population genetics is given emphasis over all other biological subfields (ARAÚJO, 2020).

Hanisch and Eirdosh (2020) provide some examples from evolution education discourse that highlight how gene-centered approaches prevail in biology curriculum standards. In the same sense, Ziadie and Andrews (2018) conducted an exhaustive systematic analysis to determine the evolutionary topics addressed in undergraduate courses on evolution. Nearly all courses covered natural selection, speciation, phylogenetics, and population genetics. Natural selection has received far more attention than other evolution topics. The authors argue and show that the current approach in evolution education entails an idealized gene-centric model to the teaching of biological phenomena, inherited from the formulation of the evolutionary synthesis.

This is problematic both from a scientific and educational point of view (LOVE, 2013). Contemporary evolutionary theory conceptualized evolution more broadly, rather than being restricted to the gene-focused approach of the so-called evolutionary synthesis. One distinctive feature of the scientific practices found in evolution is their pluralism and multidisciplinarity (ARAÚJO, 2020). As Love (2013, p. 269) points out, one key pedagogical implication from the field of evolutionary biology is that:

> Reasoning in biological science is not homogeneous; biological science is composed of multiple perspectives that correspond to diverse explanatory aims and exhibit divergent reasoning styles. We must teach the heterogeneity of reasoning in biology.

Students need to be exposed to a greater diversity of evolutionary explanations supported by a myriad of fields of studies. After all, evolution takes place at ecological and geological time scales, involving developmental, ecological, and molecular processes that interact with different levels of biological organization. Given the diversity and complexity of contemporary biology, a more pluralistic and multidisciplinary perspective to evolution education should be incorporated into teaching curricula (GEHER *et al*., 2019; HARMS; REISS, 2019).

Such a perspective also contributes to promoting the centrality of evolution in the teaching of biology (ARAÚJO, 2020). Evolutionary processes may occur in (and be applied to) numerous kinds of systems. Thus, the teaching of almost all biological disciplines can, in principle, contribute to evolutionary explanations (HARMS; REISS, 2019). A better balance between population genetics and others branches of biological sciences across curricula could be a step towards the centrality of evolution in biology teaching.

However, the broad evolutionary knowledge from different biological disciplines is not yet reflected in higher education curricula (ZIADIE; ANDREWS, 2018). In other words:

> [...] there is a major gap between the large amount of published scientific research that applies evolution across academic disciplines and the nature of undergraduate and graduate curricula at most universities. There is an urgent need to teach evolution to all students as a way to think about all biological and human-related subjects (WILSON; GEHER; WALDO, 2009, p. 4).

As far as we know, few courses effectively seek to teach evolution across biology from a multidisciplinary and pluralistic perspective. Some proposals in this regard are offered by Hanisch and Eirdosh (2020), Geher *et al.* (2019), and by the National Research Council (UNITED STATES, 2012), assembled to explore the many issues associated with teaching evolution across the curriculum. More initiatives are still needed to explore the potential opportunities of teaching evolution as a multidisciplinary and pluralistic science.

This study describes a course towards that goal, designed for the continuing education of biology students. Course participants are undergraduate students of biological sciences at different academic levels and postgraduates from public and private universities in Brazil – an understudied population. Most of the work on evolution education that takes students from different institutions and academic levels has been done in the United States and Europe (ZIADIE; ANDREWS, 2018).

An important feature of this course is that the responsible teachers carry out research on evolution from different theoretical and disciplinary perspectives. The teachers are doctoral students and recent doctors of the departments of genetics, paleontology, botany, ecology, microbiology, zoology, education, and philosophy at a public university in southern Brazil. Therefore, this multidisciplinary initiative includes the following features:

1. Theoretical and disciplinary pluralism. A group of doctoral students who conduct research on evolution across different biological disciplines is responsible for the activities. Proponents from different areas of knowledge incorporate a multidisciplinary dimension of the course, reducing the focus on genetic aspects of microevolution and natural selection, as occurs in gene-centered approaches (ARAÚJO, 2020; ZIADIE; ANDREWS, 2018).
2. Discussions beyond biology. Doctoral students in the humanities who research evolution also offer activities on socio-scientific issues related to evolution, history, and philosophy of evolutionary theory, and on conceptual aspects of evolution.
3. Challenges to teaching and learning of evolution. The course presents a critical exploration of the dilemmas faced by teachers concerning the processes of teaching and learning evolution; an analysis of the teaching materials commonly used in Brazilian basic education; and a discussion on common misconceptions about evolution as reported in the literature.

Although the multidisciplinary initiative that we discuss here does not exhaust the possibilities offered to promote the centrality of evolution in biology teaching, it provides an interesting case study to investigate how this perspective can affect evolution education. In addition to being historically important and justified in epistemological terms (ARAÚJO, 2020; DOBZHANSKY, 1973; LOVE, 2013), many researchers argue that the centrality of evolution in biology teaching would improve the quality of evolution education. This argument has been expressed, sometimes more explicitly (DOBZHANSKY, 1973; WEI; BEARDSLEY; LABOV, 2012; WILSON; GEHER; WALDO, 2009), sometimes more implicitly (APODACA *et al*., 2019; HARMS; REISS, 2019; PRICE; PEREZ, 2016).

Therefore, considering the importance of the issues mentioned above, the research objectives and related research questions that guided the study were as follows:

i. *To evaluate the key elements of the course program that contributes to the centrality of evolution in biology*. What are the challenges and opportunities for teaching evolution as a multidisciplinary and pluralistic science?
ii. *To evaluate and compare the impact of the course on students' knowledge of evolution from different biological disciplines*. Do biology students have a view of evolution restricted to specific biological disciplines? Does the course help students achieve an understanding and appreciation of evolutionary concepts from different scientific fields?
iii. *To evaluate and compare the impact of the course on students' misconceptions about evolution*. Does this course challenge misconceptions identified in students' pre-course responses?

Methodology

Course design

Since 2014, the biannual one-week (30-hours) course is offered in Porto Alegre, the southernmost capital of Brazil. A multidisciplinary group of teachers was consolidated to cover the main branches of biology and deliver some discussions related to humanities. Throughout the course's last editions, more than 400 people signed up for attending it, one hundred of them being selected. School teachers, followed by undergraduate and graduate biology students have a preference in the selection. The order of registration (date and time) serves as a tiebreaker.

The main feature of the course is that each teacher addresses evolutionary concepts and examples that connect to their field of expertise, either because it was developed by researchers belonging to the given discipline, or because it deals directly with phenomena related to their objects of study. This means of organizing the course represents an effort to address evolution across biology, with the contribution of experts who bring evolutionary considerations from their fields of expertise.

Although there are interactions among teachers and many course activities are developed in partnership, integrations are still quite restricted. Given the fact that the course took place over 30 hours, and with approximately one hundred students at a time, most activities occurred in an expository way. Conveying the diversity of kinds of reasoning found in contemporary biology to students poses concrete pedagogical challenges, not just to co-design and co-teach the course, but also ones related to methodological and disciplinary limitations.

Given the multidisciplinary nature of the course, the best way to present the content explored in the course is through the conceptual contribution that each field of knowledge has to the activities. **Table 1** presents a description of the course's content in 2019's summer and winter editions and the main contribution from each field of knowledge. These editions are the focus of this research and were chosen for the convenience of sample collection. Approximately equal time is devoted to each field of knowledge.

Table 1 – Course contents in 2019's summer and winter editions

Field of knowledge	Evolution content
Botany	Phylogeography; Diversification and plant species diversity; Examples of evolution from subtropical grasslands in the southern highlands of Brazil.
Ecology	Niche construction; Organism-environment interactions; Morphological evolution and biogeography; Examples of evolution in neotropical rodents.
Evolution education	Misconceptions about phylogenetics; A critical analysis of biology textbooks; Report of teaching experiences and teaching-learning challenges in evolution.
Evolutionary developmental biology	Epigenetics; Hox genes; Gene expression and evolution; Phenotypic plasticity; Developmental drive and constraint.
Genetics	Molecular evolution; Horizontal gene transfer; Examples of evolution in neotropical Drosophila species.
History and Philosophy of Science	Genecentrism and adaptationism: Evolutionary Biology in Brazil: Fritz Müller, voyages of Alfred R. Wallace, Charles Darwin and Theodosius Dobzhansky.
Microbiology	Symbiosis and evolution; Endosymbiont theory; Wolbachia interactions and evolution; Origin and evolution of HIV.
Paleobiology	Macroevolutionary processes and patterns; Punctuated equilibrium theory; Vertebrate evolution from the Late-Triassic Santa Maria Formation, in southern Brazil.
Socio-scientific issues	Gender and race issues in evolutionary biology; Biological evolution and post-truth; Creationism and intelligent design.
Zoology	Examples of morphological evolution from Brazilian zoological research. Cultural and behavioral evolution.

Source: prepared by the author.

Note that the course does not intend to emphasize natural selection, genetic variation, or adaptation, although these concepts are brought up all the time during the activities. Themes such as population genetics are not the central focus; rather, horizontal gene transfer and their evolutionary implications, contributions of paleobiology to macro evolutionary patterns, organism-environment interactions, the role of symbiosis in evolution, among others, are explored over the course.

In addition to this wide range of discussions on biology, the course also provides activities on controversial social issues and historical and philosophical themes in evolution. The approach to these issues has been planned contextually, that is, from relevant social and historical issues to Brazil's current political context. As a recent example, an advocate of creationism was named to lead the agency that oversees Brazil's graduate study programs (ESCOBAR, 2020). He made the comments before a Congress on Intelligent Design held in Brazil in October 2019, an event to promote intelligent design in the country. Considering current Brazilian political events such as this one, themes like scientific denialism and the advancement of the creationist movement have been explored.

Finally, the course also explores misconceptions about evolution, encouraging students to discuss the challenges faced during their learning experiences. Discussions about evolution education, based on the broad literature on the field, are used to encourage students' participation and provide some insights from the available evidence.

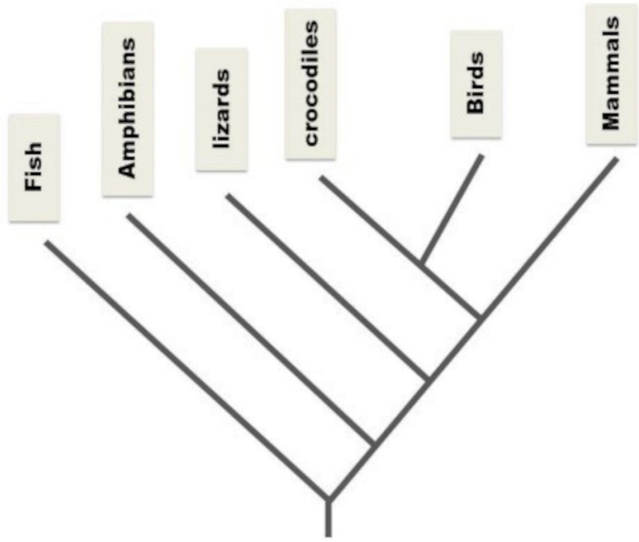
In short, the topics mentioned above and presented in **table 1** contribute to a multidisciplinary perspective of evolution education. Theoretical and disciplinary pluralism internal to biology has a much greater emphasis than a gene-centered approach, making this course a case study to investigate the challenges and opportunities offered by evolution education across biology. In addition, the course also presents discussions regarding the nature of science, social-scientific issues, and the evolution of local biodiversity. Together, the activities offer a pluralistic perspective for evolution education, especially when compared to curricula based on population genetics, as occurs in gene-centered approaches (ARAÚJO, 2020; ZIADIE; ANDREWS, 2018).

Development and validation of the research questionnaire

A questionnaire was developed and validated for this research. The first part was demographic questions. The demographic items of gender, religious affiliation, and college experience were used as grouping variables. Next, 21 items were used to measure three indicators: *misconceptions about evolution* (items A to J), *evolutionary concepts across biology* (items K to P), and *phylogenetic misinterpretations* (items Q to U). The topics therein addressed include misconceptions about natural selection, adaptation, and genetic drift; the connotation of progress in evolution; nature of science; phylogenetic misinterpretations; and some evolutionary explanations coming from developmental biology, genomics, and macroevolution as subsequently presented in **table 3**.

Students must take a position in the *phylogenetic misinterpretations* subscale based on their interpretation of a simplified evolutionary tree of vertebrates (**figure 1**). These statements present misinterpretations that are commonly found in the literature, except item Q, which denotes a correct reading of kinship relationships.

Figure 1 – Simplified phylogeny of vertebrates used to answer phylogenetic misinterpretations subscale (items Q to U)



Source: prepared by the author.

We pilot tested this survey among 119 individuals recruited in previous editions of the course. A pool of items was developed and refined considering the test, being submitted to a panel of twenty experts for review and evaluation. Based on the theoretical analysis of seven experts who returned the assessment, the validity coefficient for each item was calculated (HERNÁNDEZ-NIETO, 2002). Taking into consideration the analysis and judges' suggestions, were selected items' wordings that had the highest clarity and coefficient of representation, composing the final questionnaire. Cronbach's coefficient α was used to calculate the internal consistency coefficients of the items, for which the overall instrument had acceptable reliability (α = 0.73).

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For each assessment item, a four-point Likert scale was used. The responses were categorized into agreeing (*e.g.*, agree and strongly agree) and disagreeing (*e.g.*, disagree and strongly disagree) for the statistical analysis. Chi-Square tests (χ2) were performed to compare frequencies of responses between groups of students, separated by their level of biology training. Analysis of variance (ANOVA) was performed to compare the average of each subscale. These analyses were performed using the Statistical Package for Social Science (SPSS) software, version 18.0. The impact of the course was calculated using Hake's formula of gain index (g), by comparing normalized pre-and post-test results (HAKE, 1998). Gain-index categories were assessed as *high* for values > 0.7; *medium* for values between 0.7 and 0.3; *low* for values < 0.3; and *no gain* for values <= 0.

Both pre- and post-course questionnaires consist of the same items, but after the completion of the course, students provide additional information about differences and similarities between the learning experience in the activities and their previous instruction. Then students received the following open question with the post-course questionnaire: *What are the differences and similarities between your previous instruction in evolution and the course learning experience?*

Subjects

Students' level of biology training was classified into three groups:

1. *Biological Novices*: undergraduate biology majors in their first or second year;
2. *Biological Advanced*: undergraduate biology majors from the third year who have taken courses on evolution;
3. *Biological Graduate*: graduate biology majors in master or doctoral degree programs.

There were approximately 200 students in 2019's summer and winter editions. However, considering the inclusion criteria, and the fact that not all students completed the questionnaire, we obtained 122 pre-course and 95 post-course survey responses. **Table 2** describes participants' profiles in relation to gender, religion, and level of biology training.

Table 2 – Distribution of pre- and post-course respondents about gender, religion, and level of biology training

		Pre-course (n = 122)	Post-course (n = 95)
Gender	Female	86 (70.5%)	72 (75.8%)
	Male	36 (29.5%)	23 (24.2%)
Religion	None	99 (81%)	79 (83.2%)
	Catholic	10 (8.2%)	7 (7.4%)
	Spiritualist	5 (4.1%)	4 (4.2%)
	Evangelical	5 (4.1%)	3 (3.2%)
	Others	3 (2.5%)	2 (2%)
Level of biology training	Biological Novices	46 (37.7%)	34 (35.8%)
	Biological Advanced	42 (34.4%)	33 (34.7%)
	Biological Graduate	34 (27.9%)	28 (29.5%)

Source: prepared by the author.

It is important to highlight the disparity in proportion between females and males, as can be seen in **table 2**. Female students are more interested and enroll in the course much more than male students. Although higher education in Brazil presents a gender imbalance, where women are slightly more numerous (UNESCO, 2018), the proportion of participants in the course according to gender overrepresented such imbalance.

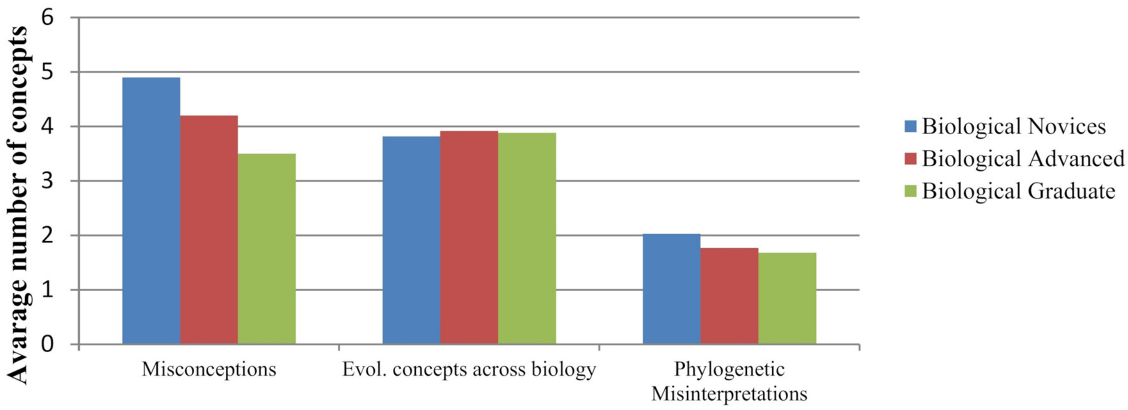
Another interesting fact is the large number of students who declared to not have a religion, a different profile from that found in surveys carried on in mandatory academic courses and with Brazilian school teachers (*e.g.*, OLEQUES; BARTHOLOMEI-SANTOS; BOER, 2011; TIDON; LEWONTIN, 2004). Such surveys found a greater number of people who identified with certain religions, mainly Catholics and Evangelicals. Since the course is an optional activity that attracts those interested in evolutionary biology, the profile of students who attend the course may present significant differences in relation to a sample that represents biology students nationwide. This attendance is further evidence that acceptance of evolution in Brazil is an important question even for teachers who opted to study biology (OLIVEIRA; COOK, 2019). Religion (or lack of religious beliefs) can be a determining factor for choosing the course.

Results and discussion

Pre-course results

Students have fewer misconceptions about evolution when they have a higher level of biology training. However, a considerable number of students fail to get rid of their misconceptions about evolution and phylogenetic misinterpretations. The *evolutionary concepts across the biology* subscale did not present differences in the average response among groups, according to the level of biology training (**figure 2**).

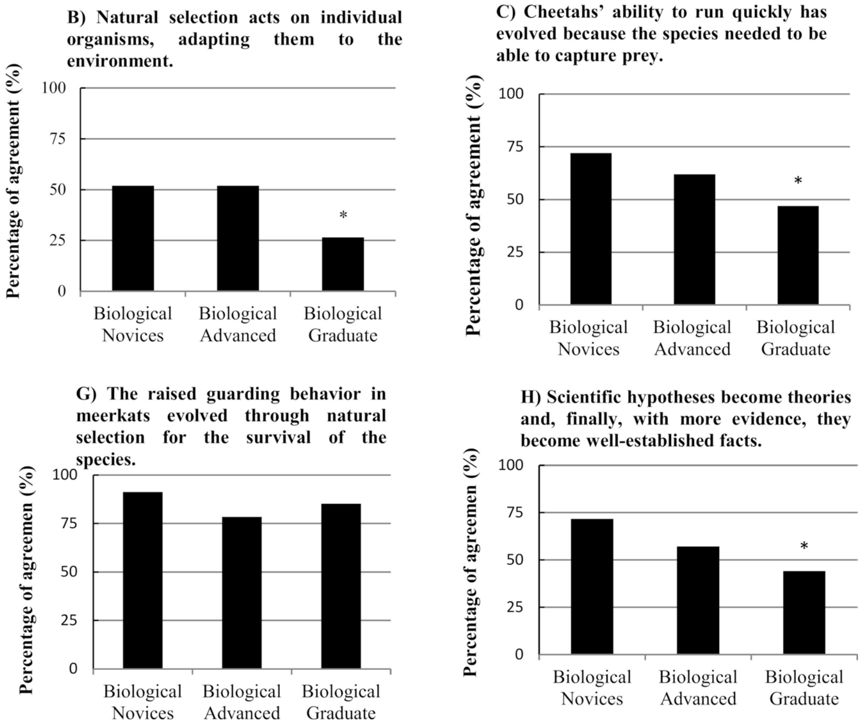
Figure 2 – Misconceptions and phylogenetic misinterpretations decrease as educational level increases, but they are still present*



Misconceptions: items A to J; Evolutionary concepts across biology: items K to P; Phylogenetic misinterpretations: items Q to U.
*Surprisingly, groups show no differences in the average response to evolutionary concepts across biology. Analysis of variance (ANOVA) indicates significant differences between the groups in the misconceptions and phylogenetic misinterpretations subscales ($p < 0.05$).
Source: prepared by the author.

The differences between novice and advanced undergraduate biology majors are minimal concerning most items. More than 50% of undergraduate biology majors agree with the misconceptions expressed in items B, C, G, and H. Item G has a very high percentage of agreement in all groups (above 75%). This stability suggests that to have taken an evolution course does not undo some fundamental misconceptions presented in the questionnaire. On the other hand, graduate students show a lower rate of agreement about items B, C, and H, differing significantly. However, the percentage of agreement is still relatively high, especially in item C, with a prevalence of 47% (figure 3).

Figure 3 – Pre-test percentage agreement (n = 122), according to the level of biology training



*p < 0.05.
Biological graduate students differ from biological novices in items C (χ2 = 4,955 p = 0.026) and H (χ2 = 6,215 p = 0.013). Biological graduate students differ from both groups of undergraduate students in item B.
Source: prepared by the author.

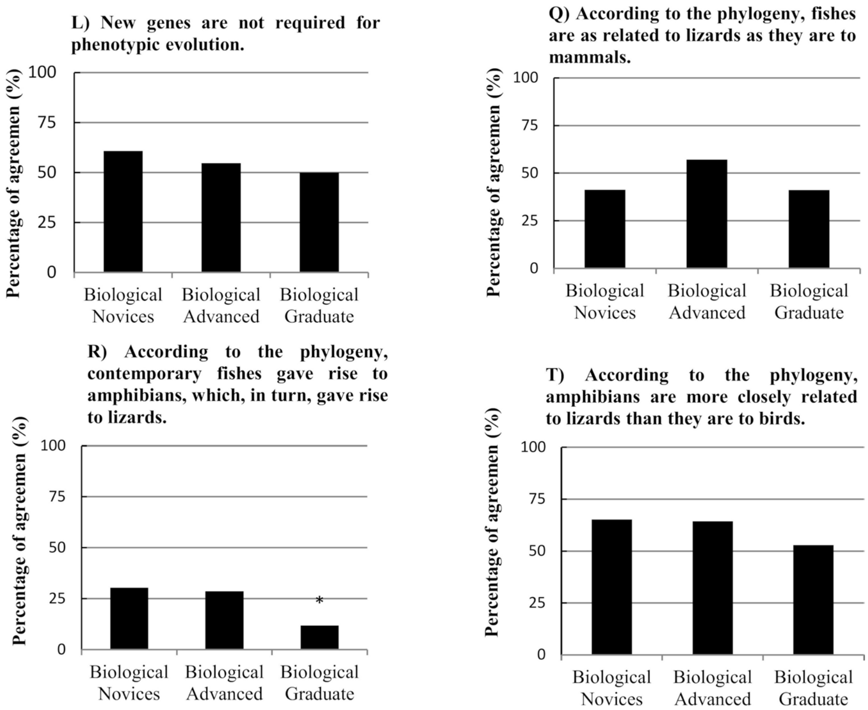
Except for item H, all the others shown in Figure 3 are misconceptions about natural selection. These items cover common misconceptions, such as the notion that natural selection involves organisms trying to adapt, or the idea that natural selection gives organisms/species what they need. Previous research has also shown a high prevalence of such misconceptions among students at all levels (BISHOP; ANDERSON, 1990; FERRARI; CHI, 1998; GREGORY, 2009; NEHM; REILLY, 2007).

Although students at the graduate level showed a relatively low level of *misconceptions about evolution*, they do not differ from other groups in *evolutionary concepts across biology*, with items related to developmental biology, genomics, paleobiology, and macro-evolution. It is reasonable to expect that students would know more about evolutionary explanations with a higher their level of biology training. However, their responses do not confirm such an assumption.

In this regard, it is worth mentioning the percentage of agreement for item L, which contrasts with the gene-centered view of evolution. Biological graduate students show a lower rate of agreement for this item when compared to other groups (**figure 4**). This result makes sense if we consider that syllabuses often present genetics as being fundamental to all other biological disciplines when it comes to evolution (ARAÚJO, 2020; BIZZO; EL-HANI, 2009). Thereby, a gene-centered view of evolution seems to be reinforced throughout academic training.

Although the level of biology training does not help students achieve an understanding of *evolutionary concepts across biology*, it has some relevance when it comes to *phylogenetic misinterpretations*. The last five items of the questionnaire present statements about relationships established in a phylogeny of vertebrates. One of them showed a significant difference: undergraduate biology majors (novices) agreed more with item R than graduate students. On the other hand, Q and T items frequencies reveal that a large proportion of students, regardless of their level of biology training, do not read the kinship relations from the branching pattern of the phylogeny (**figure 4**).

Figure 4 – Pre-test percentage agreement (n = 122), according to level of biology training



Biological graduate students differ from biological novices in item R ($\chi 2$ = 3,908 p = 0.048).
Source: prepared by the author.

Some general conclusions can be drawn from the comparative analysis. First, misconceptions about natural selection and adaptation are the most common among students. While graduate students present a decrease in the level of misconceptions, undergraduate biology majors do not show a substantial change. This result indicates that misconceptions may persist without improvement despite formal undergraduate instruction in evolution.

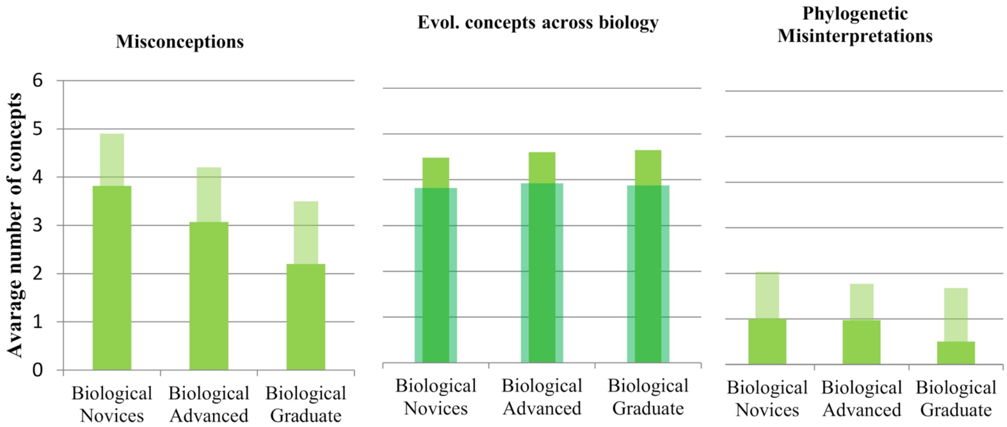
Second, students do not expand their repertoire of evolutionary concepts across biology when they increase their level of biology training. On the contrary, a gene-centered view of evolution becomes more prevalent, despite contemporary discussions on evolutionary developmental biology and genomics that challenge it. Third and finally, the academic level does not consistently improve the understanding that the branching pattern of a phylogeny indicates taxon relatedness.

Pre- and post-course comparison

The effectiveness of the course in challenging misconceptions and increasing understanding of evolutionary concepts across biology can be measured through the variation in the number of correct answers in the pre- and post-course questionnaire.

Comparisons between pre- and post-course performances show a significant overall increase in students' knowledge: we observed a decrease in *misconceptions* and *phylogenetic misinterpretations* in all groups and an increase in the *evolutionary concepts across biology* (**figure 5**).

Figure 5 – Students from all levels of biology training benefit from a teaching approach that takes evolutionary theory across biological disciplines. Light green shows the average number of pre-course and solid green of post-course concepts



Source: prepared by the author.

Comparison between pre- and post-course correct responses for each item, considering all students, reveals that most items (11 statements) fall in Hake's medium-g category of knowledge enhancement. Six statements fall in the low-g category, where four of them relate to *misconceptions about evolution*. Finally, four statements fall in the high-g category, three of them being related to *evolutionary concepts across biology* (**table 3**).

Table 3 – Mean of correct responses for each item in pre-course (n = 122) and post-course (n = 95) questionnaires, considering all students

Items	Answer	Pre-course (%)	Post-course (%)	Change (%)	Gain class (g)
A. Natural selection produces organisms perfectly suited for their environment	Disagree	54.1	71.5	17.4	0.38 (medium)
B. Natural selection acts on individual organisms, adapting them to the enviroment	Disagree	55.0	63.2	8.2	0.18 (low)
C. Cheeta's ability to run quickly has evolved because the species needed to be able to capture prey.	Disagree	38.5	52.6	14.1	0.23 (low)
D. Population changes over generations are always adaptive.	Disagree	62.3	80.0	17.7	0.47 (medium)
E. Genetic drift is an evolutionary mechanism that occurs when a population is not under natural selection.	Disagree	59.9	65.3	5.4	0.73 (low)
F. Current species evolved over a long period of time and, therefore, they have more anatomical, biochemical and physiological characteristics than their ancestors.	Disagree	69.7	83.2	13.5	0.44 (medium)
G. The raised guarding behavior in meerkats evolved through natural selection for the survival of the species.	Disagree	14.8	28.4	13.6	0.16 (low)
H. Scientific hypotheses become theories and, finally, with more evidence, they become well-established facts.	Disagree	41.0	57.9	16.9	0.28 (medium)
I. The lack of fossil records for intermediate forms, as found among Homo sapiens and species of hominins, may refute the evolutionary theory.	Disagree	90.2	93.3	3.1	0.31 (medium)
J. Evolutionary theory reached its maturity with the unification of Darwinism and genetics, and has not changed since then.	Disagree	78.7	93.6	14.9	0.69 (medium)

Items	Answer	Pre-course (%)	Post-course (%)	Change (%)	Gain class (g)
K. Morphological evolution is limited by developmental and historical constraints.	Agree	65.5	71.6	6.1	0.17 (low)
L. New genes are not required for phenotypic evolution.	Agree	55.7	88.4	32.7	0.74 (high)
M. The lineages of organisms have evolved at a constant rate.	Disagree	72.2	82.1	9.9	0.35 (medium)
N. Evolutionary radiations and extinctions are important evolutionary processes.	Agree	91.8	97.9	6.1	0.74 (high)
O. There is a lot of evidence that supports the hypothesis of common ancestry between eukaryotes and prokaryotes.	Agree	90.0	97.9	7.9	0.79 (high)
P. Macroevolutionary events (on a scale above the level of populations) result from the sum of microevolutionary events (population-level phenomena).	Disagree	8.2	19.0	10.8	0.12 (low)
Q. According to the phylogeny, fishes are as related to lizards as they are to mammals.	Agree	46.7	83.0	36.3	0.68 (medium)
R. According to the phylogeny, contemporary fishes gave rise to amphibians, which, in turn, gave rise to lizards.	Disagree	75.4	92.6	17.2	0.7 (high)
S. We can infer from the phylogeny that fishes have changed little since the divergence from the common ancestor of all vertebrates.	Disagree	63.1	75.8	12.7	0.34 (medium)
T. According to the phylogeny, amphibians are more closely related to lizards than they are to birds	Disagree	38.5	69.5	31.0	0.5 (medium)
U. We can infer from the phylogeny that amphibians are less evolved than birds and mammals.	Disagree	86.1	94.8	8.7	0.62 (medium)

Source: prepared by the author.

The comparative analysis highlights that evolution education across biology can be a way of promoting knowledge enhancement in a great variety of evolutionary explanations, as expressed in the increase of correct responses to questions concerning evolutionary concepts across biology. For instance, a high rate of improvement was found in item L, which ranged from a pre-course correct response score of 55.7% to a mean post-course score of 88.4%, contrasting with the gene-centered view of evolution. A high-g was also found in items N and O, related to evolutionary irradiations and the concept of a universal common ancestor. The only exception between evolutionary concepts across biology was the item P, related to macroevolution. An error rate of above 80% remains in post-course responses.

The inherent multidisciplinary feature of the course gives students a more pluralistic view of evolution, expanding it to a wide variety of fields of knowledge. This is an important difference when compared to the initial training of students. As pre-course results showed, academic background and students' prior experiences seem to have an impact on misconceptions about evolution and phylogenetic misinterpretations, but not in evolutionary concepts across biology.

This finding is confirmed by an open question through which students are asked to reflect on the differences and similarities between their initial formation and the course's learning experience. The course is perceived differently from the initial training of students, generally associated with a gene-centric curriculum and focused on natural selection. To illustrate this assertion, consider the following responses (R1, R2 and R3) obtained in the 2019 summer edition. The quotations presented are translated from Brazilian Portuguese:

> (R1). *Yes, in both high school and higher education evolution was presented as a combination of natural selection and mutations. This course showed that there are many more elements that are involved with evolution. In addition, in biology class is common the idea that some organisms are more evolved than others, and this course helped to dismantle that idea.*

> (R2). *There are so many differences. I couldn't imagine that evolution involves so many things as evolutionary developmental biology, epigenetics, and philosophy. The course brought me a greater sense of the 'universe' of evolutionary biology.*

> (R3). *Yes, there were differences. The activities were less related to genetics and gradualism. Perhaps the main difference was that the course focuses on evolutionary processes and their relationship with ecology and development.*

The post-course results are in line with the idea that evolution education is often restricted to specific contents and concepts, as inherited from the formulation of the evolutionary synthesis (ARAÚJO, 2020; HANISCH; EIRDOSH, 2020; ZIADIE; ANDREWS, 2018). As shown in the pre-course results, the level of biology training does not have a significant impact on the repertoire of evolutionary concepts across biology, while the multidisciplinary approach presented here can be a way of promoting knowledge enhancement in a greater variety of evolutionary contents.

However, students still show resistance towards changing their misconceptions at the end of the course, especially in the items related to natural selection and adaptation. Items B, C, and G about natural selection maintain above 30% of error rate in post-course responses. Some studies seek to associate a poor understanding of natural selection with students' acceptance of evolution or religious beliefs (BUCKBERRY; SILVA, 2012). However, the acceptance of evolution is not a relevant factor among course students, since the activities are elective and the vast majority claim to have no religion. A multidisciplinary approach in itself is not enough to challenge misconceptions about evolution, demanding some other subjects or new ways in which teaching can be organized.

Despite the minor impact on misconceptions about natural selection, the course has shown to have had a greater impact on phylogenetic misinterpretations. After the course, there was an increase of above 30% in correct answers for items Q and T, related to kinship relationships. This improvement can be explained by the specific activities offered on phylogenetic interpretation. A brief introduction to evolutionary trees and some basic details on how they should and should not be read and interpreted is present in all editions of the course. This is followed by a discussion of the most common misconceptions about evolutionary trees as reported in the literature (*e.g.*, BAUM; SMITH; DONOVAN, 2005; GREGORY, 2008; MEAD, 2009; MEIR *et al.*, 2007).

In addition, the course explored fossil evidence and deep time as sources of evolutionary data in a guided visit to a free exhibit on the Museum of Paleontology at Federal University of Rio Grande do Sul. With this visit, the contingent feature of evolution becomes clear through the observation of most of the important events in evolution. The combination of an overview of the patterns that represent the history of life and activities that deal directly with phylogenetic misconceptions seemed promising to solve the misinterpretations explored in the questionnaire. Up to this point, natural selection and adaptation were not broadly covered, which may explain the low impact of the course concerning these evolutionary concepts.

It should be taken into account that, explicitly or implicitly, the term 'misconception' carries the expectation that students' previous ideas should be abandoned in the learning process. However, we agree with Mortimer (2000) regarding the fact that it would not be adequate to reduce the learning process to a replacement of students' previous ideas with scientific ones.

Limitations and suggestions for further research

The course has gone through several challenges related to co-designing and co-teaching, as well as to cope with methodological and disciplinary limitations. Hence, we need to reflect on some of such limitations. One of them concerned the relatively small number of respondents to the questionnaire (122 pre-course and 95 post-course), divided into three groups according to their level of biology training. Despite the comparison of pre-test and post-test, a retention test would also be necessary to show the consolidation of learning after instruction. In addition, this study used the same measuring instruments for pre- and post-test, which can provide a 'remembering effect', that is, the post-test results can have been affected by those from the pre-test.

A greater number of responses would be desirable to make the comparisons more reliable. In addition, the questionnaire could present more evolutionary concepts across biology in order to cover a wider range of contents. However, since the questionnaire was already quite multi-thematic, it was difficult to further expand it to other topics.

Another limitation was the duration of the course: only 30 hours, condensed into one week. This type of intervention is unrealistic in pedagogical terms. Consequently, the educational format is limited in terms of bolstering and perpetuating the interdisciplinary nature of evolutionary theory. Furthermore, making integrations and links between disciplines into a coordinated and coherent whole cannot be left out when talking about interdisciplinary (LOVE, 2013). Although there are interactions among teachers in the course and many activities are developed in partnership, integrations are still quite restricted. Therefore, course organization is closer to a multidisciplinary practice, that is, it "[…] draws on knowledge from different disciplines but stays within the boundaries of those fields" (ALVAR GONZÁLEZ, 2011, p. 388).

Unfortunately, to produce a study with none of these limitations is not accessible to us. Thus, we hope that the results from this exploratory study about the impact of a learning project on evolution across biology in higher education can bring up possibilities for later improvement.

Nevertheless, this research study also offered some unique features. The first is the study population of the course: the activity represented a special opportunity to investigate students at different levels of biology training and from different Brazilian higher-education institutions. Most of the work on evolution teaching that considered students from different institutions and academic levels was done in the United States and Europe (ZIADIE; ANDREWS, 2018). Few studies of this type have been carried out in Brazil, or even in Latin America as a whole. Another advantage is that the research instrument has gone through development and validation processes, with the contribution of experienced researchers. The pluralistic aspect of the questionnaire, although methodologically challenging, is innovative in disciplinary terms.

To improve the quality of the results, further research could include a larger number of participating students and a comparison group of students that did not attend the course, in addition to a great number of repetitions of interventions. It is also desirable to create and investigate curricular proposals for evolution across biology in terms of the standard higher education curriculum and not just within a semester or in a condensed course like the one presented here.

Conclusions

Many researches on biology education argue that the centrality of evolution in biology teaching represents many advantages. Justifications come from different sources, based on epistemological, historical, and pedagogical grounds (ARAÚJO, 2020; DOBZHANSKY, 1973; WEI; BEARDSLEY; LABOV, 2012; WILSON; GEHER; WALDO, 2009).

However, few studies propose concrete activities in this direction, and even a smaller number of studies investigate the impact of such an approach. The course described here presents a multidisciplinary initiative that is based on the centrality of evolution in biology teaching, being an interesting case study to investigate how this perspective can impact evolution education.

As our results indicate, students of all levels of biology training benefit from a teaching approach of evolutionary theory across biological disciplines. The pre-course results show that level of biology training does not help students have a broader knowledge of evolutionary theory, which may be one of the main advantages of a teaching approach to evolution across biology.

Nevertheless, the impact of this approach is still conflicting when it comes to misconceptions about evolution. Although a multidisciplinary perspective improves the understanding of phylogenies – which demand knowledge about biodiversity and macro-evolution – it seems to have a small impact on misconceptions about natural selection and adaptation.

It must be considered that the course is an activity of only 30 hours duration, so that it is necessary to evaluate its impact in a broader pedagogical context. School curricula must be addressed in order to effectively insert evolutionary theory across all biological disciplines and, to the extent of some discussions, across humanities in general. In any case, it is important to keep in mind that the centrality of evolution in biology teaching is not necessarily a panacea for the multiple issues of current evolution education.

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