doi: https://doi.org/10.26529/cepsj.1508

The Impact of Exploring Sexual Selection on Primary School Students' Understanding of Evolution

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Several researchers and scientific institutions argue that evolution should be explored from the first school years. However, few studies have analysed primary school students' understanding of evolutionary processes or evaluated the impact of educational activities on such knowledge. The available data: i) suggest that primary school students can learn about evolution; and ii) identify differential reproduction as the key evolution concept less often used by students to make and justify evolutionary predictions. In the present study, we evaluate the impact of an educational programme on primary school students' level of understanding of evolution by sexual selection and on their ability to employ differential reproduction to propose and justify evolutionary predictions. An evaluation framework was applied to estimate primary school students' level of understanding of evolution by sexual selection in third- and fourth-grade classes, before and after the students were exposed to the educational programme. A significant increase in the level of understanding of evolution by sexual selection was observed in the target classes, but not in the control classes. This result was primarily driven by a significant increase in the students' justifications employing the concept of differential reproduction. The results suggest that activities that model and simulate biological evolution through sexual selection can contribute to primary school students' understanding of evolutionary processes.

Keywords: primary school, sexual selection, evolution education, conceptual understanding, model-based learning

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Vpliv raziskovanja spolne selekcije na razumevanje evolucije pri osnovnošolcih

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Več raziskovalcev in znanstvenih ustanov trdi, da je treba evolucijo raziskovati že v prvih šolskih letih, vendar pa je malo študij analiziralo razumevanje evolucijskih procesov pri osnovnošolcih ali ovrednotilo vpliv izobraževalnih dejavnosti na tako znanje. Razpoložljivi podatki: i) nakazujejo, da se osnovnošolci lahko učijo o evoluciji; ii) opredeljujejo diferencialno reprodukcijo kot ključni koncept evolucije, ki ga učenci redkeje uporabljajo za navedbo in utemeljitev evolucijskih napovedi. V tej študiji ocenjujemo vpliv izobraževalnega programa na raven razumevanja osnovnošolcev glede evolucije s spolno selekcijo in na njihovo sposobnost uporabe diferencialne reprodukcije za predlaganje in utemeljitev evolucijskih napovedi. Pri tem je bilo uporabljeno evalvacijsko ogrodje za oceno stopnje razumevanja evolucije s spolno selekcijo osnovnošolcev v oddelkih tretjega in četrtega razreda, pred tem in po tem, ko so bili učenci izpostavljeni izobraževalnemu programu. Znatno povečanje stopnje razumevanja evolucije s spolno selekcijo so opazili v ciljnih, ne pa tudi v kontrolnih razredih. Ta rezultat je bil predvsem posledica znatnega povečanja utemeljitev učencev, ki uporabljajo koncept diferencialne reprodukcije. Izsledki kažejo, da lahko dejavnosti, ki modelirajo in simulirajo biološko evolucijo s spolno selekcijo, prispevajo k razumevanju evolucijskih procesov pri osnovnošolcih.

Ključne besede: osnovna šola, spolna selekcija, evolucijska vzgoja, konceptualno razumevanje, modelno učenje

Introduction

Although evolution understanding is fundamental for students in order to address important sustainability problems (Jørgensen et al., 2019), several studies show that many people are unable to understand, or even to accept, evolution (see, for example, Miller et al., 2006; Kuschmierz et al., 2021).

In order to overcome this problem, several researchers and scientific institutions argue that evolution is a core idea around which learning progressions in biology should be built from the first school years (Nadelson et al., 2009; National Research Council [NRC], 2012, 2013; Wagler, 2010, 2012; see also the review of Treagust & Tsui, 2013 by Torkar, 2017). Despite this, few studies have analysed the ability of primary school students to learn about evolution, or evaluated the impact of educational activities on primary school students' understanding of evolutionary processes (see, however, Berti et al., 2015; Brown et al., 2020; Campos & Sá-Pinto, 2013; Emmons et al., 2017; Kelemen et al., 2014; Sá-Pinto et al., 2021a). In a systematic literature review conducted by Bruckermann et al. (2020), aimed at identifying which precursory concepts in evolution early childhood and primary school children already possess or develop after an educational intervention, the authors found that even children aged up to seven years are able to understand the basic mechanisms of the core concepts in evolution, such as variation, inheritance and natural selection. Grether (2021) used lesson plans with active learning activities to teach specific evolutionary learning objectives (fossils, vestigial traits, common ancestry, heritability, natural selection and evolutionary time) to primary school students (grades 3–5). This author reports a substantial improvement in the students' understanding of evolutionary concepts after engaging in these activities. Using a storybook intervention that explored the concepts of intraspecific diversity, heredity, environmental change, differential survival, differential reproduction and frequency change over generations, two studies show that kindergarten and primary school students can learn about evolution by natural selection (Emmons et al., 2017; Kelemen et al., 2014). Sá-Pinto et al. (2017a) proposed a framework to evaluate primary school students' level of understanding of evolution by natural selection and Sá-Pinto et al. (2021a) adapted it to evaluate an educational transdisciplinary activity that used a problem-based learning approach to teach fourth graders about natural selection and numerical sequences related to geometric growth. This study shows that primary school students can learn about evolution and are able to apply the key concepts related to natural selection (selective pressure, differential survival, differential reproduction, frequency change; following Tibell and Harms, 2017) to explain or predict biological scenarios (see Mestrinho et al., 2023 for students' mathematics learning). A study by Brown et al. (2020) also shows that, although primary school students reveal some common evolution misconceptions, these are easily overcome with instruction, a picture that strongly contrasts with what is known regarding older students, whose misconceptions are shown to resist instruction (Bishop & Anderson, 1986; Nehm & Reilly, 2007). Although these studies support primary school students' ability to learn about natural selection, the results of Sá-Pinto et al. (2017a, 2021a) show that differential reproduction is not frequently mentioned by students. This is particularly worrying, as differential reproduction is the most important parameter determining individuals' fitness, and because students tend to believe that fitness is determined by the individual's ability to survive, their strength or intelligence (Gregory, 2009). These results highlight the importance of further exploring the concept of differential reproduction. Recently, Sá-Pinto et al. (2017b) have argued that exploring sexual selection may help students to further understand evolution, as this process focuses on the parameter that defines an individual's fitness: its reproductive output.

Although sexual selection was only named later (Darwin, 1871), the importance of this process for species' evolution has been recognised since the first joint publication of Darwin and Wallace (1858). In this publication, Darwin wrote that »Besides this natural means of selection, by which those individuals are preserved, whether in their egg, or larval, or mature state, which are best adapted to the place they fill in nature, there is a second agency at work in most unisexual animals, tending to produce the same effect, namely, the struggle of the males for the females. These struggles are generally decided by the law of battle, but in the case of birds, apparently, by the charms of their song, by their beauty or their power of courtship, as in the dancing rock-thrush of Guiana. The most vigorous and healthy males, implying perfect adaptation, must generally gain the victory in their contests. This kind of selection, however, is less rigorous than the other; it does not require the death of the less successful, but gives to them fewer descendants« (Darwin & Wallace, 1858, p. 50).

Since Darwin's first description, the process of sexual selection has been strongly debated by the research community, with several authors arguing that it would be a component of 'broad sense' natural selection (reviewed by Andersson, 1994; Shuker & Kvarnemo, 2021). Several studies have supported the importance of the competition for mates in species evolution and speciation processes (reviewed by Andersson, 1994; Andersson & Simmons, 2006). Furthermore, the effect of sexual selection in some traits opposes the effect of natural selection (when defined in its 'narrow sense' emphasising the viability or fecundity components of fitness; this definition of natural selection will be used throughout the present article) as it occurs, for example, in the evolution of ornaments (reviewed by Andersson, 1994; Shuker & Kvarnemo, 2021). Given this, the concept of sexual selection has been retained and is widely used to refer to the fitness component related to success in the competition for access to mates, or gametes. Andersson defined sexual selection in a trait as »differences in reproductive success, caused by competition over mates and related to the expression of the trait« (Andersson, 1994, p. 7). More recently, Shuker and Kvarnemo have proposed an alternative definition of sexual selection as »any selection that arises from fitness differences associated with non-random success in the competition for access to gametes for fertilisation« (Shuker & Kvarnemo, 2021, p. 781), thus emphasising that, although access to mates (pre-copulatory mating success) may be the first step, sexual selection can still occur after mating (post-copulatory mating success). Several factors may affect the strength of sexual selection acting in a sex, including sex differences in parental investment, mating systems, sex ratios or operational sex ratios (extensively reviewed by Andersson, 1994 and summarised in Sá-Pinto et al., 2017b). Although females are often the limiting sex for reproduction (thus imposing a stronger sexual selection in males), there are numerous exceptions to this pattern (see examples in Sá-Pinto et al., 2017b). Sexual selection will favour traits that improve the ability of individuals of a sex to maximise their access to mates (or gametes). These include traits that allow them to find mates faster than others, to attract more (or better) partners of the limiting sex, to keep rivals away, to keep reproductively active for a longer period, and to produce more gametes (summarised in Sá-Pinto et al., 2017b). Importantly, favoured traits may act before and/or after copulation, as pointed out by Shuker and Kvarnemo (2021).

The teaching of sexual selection is fundamental for students to make sense of the surrounding world. Palanza and Parmigiani (2016) argue that the combined teaching of sexual and natural selection is fundamental for medicine and psychology students to understand the anatomy, physiology and behaviour of humans, the selective pressures that condition the evolution of these features, and how the mismatch between past and present conditions cause human vulnerabilities to diseases and behavioural disorders.

Despite the importance of sexual selection for biological processes and for fostering students' understanding about these processes, few educational activities designed to promote learning about this process are described, and even fewer studies have analysed students' knowledge or ability to learn about this process (reviewed in Sá-Pinto et al., 2017b). Kalinowski et al. (2013) describe six activities that were implemented with students in introductory biology courses to promote their learning about evolution by natural selection. One of them was a class discussion related to peacock feathers, in which students were asked to propose explanations for the evolution of this trait before and after being presented data regarding female mating preferences. The other activities explored the selection of dog breeds to introduce the concept of selection, the coat colour in oldfield mice (*Peromyscus polionotus*) to introduce the sources of variation, human evolution to introduce natural selection, antibiotic resistance to introduce complex traits evolution, and the apparent suicide of lemmings to introduce behavioural evolution. The authors show that, after exploring this pack of six activities, students increased their understanding of natural selection. Luttikhuizen (2018) described a card game for students to learn about processes that are frequency dependent, including cases of sexual selection. Although the authors do not present data for the students' learning evaluation, they report that these activities were successfully explored with university students. Kane et al. (2018) developed a series of activities for middle school students to use trinidadian guppies (live animals and models of the species *Poecilia reticulata*) to explore several evolutionary processes, including sexual selection (through mathematical modelling situations). Although the authors did not evaluate the impact of the activities on students' learning, both teachers and students praised these activities. Bouwma-Gearhart and Bouwma (2015) also propose using live crickets from the species *Acheta domesticus* to help students build progressively better models of evolution that account for both natural and sexual selection, as well as the interplay between these two processes, an approach that was applied to high school and university students. However, no information is provided on how these activities contributed to students' learning. Fee and Alfano (2013) propose a set of activities that explore several species of birds of paradise as models for students to learn about both natural and sexual selection. Lawson (2003) proposed an activity to be explored by sixth graders or older students that uses coins to model evolution by sexual and natural selection. Sá-Pinto et al. (2017b) propose two activities for students to learn about sexual selection by mate choice and male-male competition that model these processes through a card game and balloon sword contests. These few studies show that: i) most of the activities were proposed and implemented with older students (university and high schools); ii) the impacts of the activities on students' learning are most often assumed rather than evaluated. The latter means that no information is available on the impact of exploring sexual selection on primary school students' understanding of evolutionary processes. In the present study, we aim to contribute to overcoming this lack of information by studying: i) whether activities modelling biological evolution through sexual selection can assist primary school students to learn and apply the concept of differential reproduction; and ii) whether these students can understand the processes of sexual selection and apply this knowledge to predict biological scenarios.

Method

Educational activity

In order to promote students' learning about evolution by sexual selection, we planned an educational programme that included four sessions of approximately two hours each. The first and second sessions were introductory sessions exploring two key principles that, according to Tibell and Harms (2017), are fundamental to understanding evolution: the variation principle and the heredity principle. To explore the variation principle, the students explored the intraspecific variability in humans through an activity adapted from Campos and Sá-Pinto (2013). In a class discussion, the students were initially asked to identify variable human traits. In small groups, they were then asked to choose two traits from those initially listed to describe, categorise, quantify and depict the different phenotypes, and to group their classmates according to these phenotypes. During this activity, the students mentioned and explored mostly observable traits (such as skin, hair and eye colour, height, etc.), but traits such as 'voice' and 'blood types' were also mentioned and analysed. At the end of the session, the students were asked to observe the chosen traits in their family members and to register the information in a genealogical tree provided to them. The genealogical trees were used in the second session to explore the principle of heritability. Following Campos and Sá-Pinto (2013), we asked the students to analyse with whom they each shared a higher number of features and, for each feature, which of their family members displayed such features. After the students noticed that some phenotypes 'jumped' generations, the researchers explored with the children the concept of dominant, recessive and co-dominant phenotypes, using blood types and imaginary genealogical trees to exemplify the transmission and expression of these features.

The students were only introduced to sexual selection in the third and fourth sessions, through two activities that model a scenario of mate choice and male competition, as described by Sá-Pinto et al. (2017b). Briefly, in the activity of the third session, the students were asked to model sexual selection occurring in a male-biased population. They played the role of the females and were asked to choose their mates from a pool of cards that initially displayed four distinct and equally frequent phenotypes. The individuals chosen reproduce, each giving rise to three fertile descendants (one female – the student – and two males – two cards with the same phenotype of the one chosen by the student) and then die. This model was used for three generations. The frequency of each phenotype in each generation was recorded on the blackboard and the changes observed across generations, as well as the causes for those changes, were discussed with the entire class. In order for students to understand how the sex ratio could affect the strength of sexual selection, the same model was applied to a scenario in which the students were at the same number of the cards. The results of this scenario were compared to those previously obtained and the reasons for the differences were discussed in the classroom. Some examples of species with biased and unbiased sex ratios and their sexual dimorphism were then presented to the students using a resource provided by Sá-Pinto et al. (2017b). In the fourth session, the students explored intrasexual competition, modelling this process through balloon sword fights. They were asked to play the role of males who had to fight with other males to secure access to mates with balloon swords that modelled a body feature such as horns or antlers. Balloon swords of two very distinct sizes were randomly assigned to the students, who were randomly assigned to pairs. In each pair, the student who first touched their opponent three times with their sword wins and reproduces leaving two descendants with a sword of the same size as their parent's sword. The student who loses the fight does not reproduce her/his sword. In each generation, the frequency of the size of the swords, which was initially equal, was registered on the board and the reasons for the frequency changes observed across generations were discussed with the students.

Evaluation of students' understanding of evolution by sexual selection

The sessions were applied in a convenience sample of one third-grade class (N = 19, ages ranging from 8 to 9 years old) and one fourth-grade class (N = 15, ages ranging from 9 to 10 years old) recruited from a Portuguese public school. Informed consent to perform the study and collect the students' answers was obtained from the students' legal guardians. Consent to perform the study was also obtained from the teachers and the school board. No personal data was collected from the students, who were identified only with a code number.

The students were tested for their ability to use knowledge on sexual selection to predict the evolutionary outcome of a biological system two days before and one day after the sessions. The evaluation instrument was inspired by the one proposed by Sá-Pinto et al. (2017a), but adapted to a sexual selection scenario. The test introduced students to a beetle population (see Figure 1a), initially presenting polymorphism in males' mandible sizes. The students were asked to predict the frequency of the jaw sizes after one hundred years, knowing that: i) male beetles used their mandibles to fight other males and move them away from females; ii) each beetle only lives one year; and iii) mandible size is a heritable trait. The English translation of the test presented to the students can be found in Figure 1a. The test was read aloud to the entire class, and the researchers further clarified the task orally by asking the students to make their predictions and justifications considering the three mandible male phenotypes already depicted in the figure. The researchers also clarified the meaning of some terms, such as mandibles. The students were asked to draw and provide a written justification for their predictions, and were given 15 minutes to complete these tasks. Following Sá-Pinto et al. (2017a), after the tasks were completed, each student was asked to verbally explain their predictions and their justifications before handing in the test. Irrespective of the type of student answer, when the students verbally provided more information to the researcher than was written or drawn on the test, they were asked to add that information to their answer. Approximately 30 minutes were necessary for all of the students to complete this process in each class. The pre- and post-tests were similar. Control classes were used to verify the impact of the students' double exposure to the test and to evaluate the internal validity of the process (Lahm, 2004). The two control classes (one third- and one fourth-grade class) were from the same school as the target classes, but were not exposed to the educational programme. The tests were applied on the same days in all of the control and target classes. No significant differences were found between pre- and post-test in the control classes, thus ensuring the internal validity of our evaluation instrument (Lahm, 2004).

The students' answers were analysed using content analysis. The key concepts related to the selection dimension proposed by Tibell and Harms (2017) were used as categories of the analysis: selective pressure; differential survival; differential reproduction; trait relative frequency change in population (Table 1). We did not look for evidence of students mentioning speciation as divergence between populations, as it was not an expected outcome from the proposed biological scenario. Furthermore, we did not evaluate the key concepts related to the dimensions of heredity and variation, as, following Sá-Pinto et al. (2017a, 2021a), the information related to these key concepts was provided to the students in the test. The expected fittest phenotype was considered to be the larger mandibles, unless the student provided information in the answer to support a credible biological scenario in which other phenotypes increase the progeny of the individuals more than the larger mandibles.

Table 1

Categories of the content analysis, their definition and examples of answers attributed to each category of the analysis. The section of the answer that justifies its attribution to the specific category is highlighted in bold

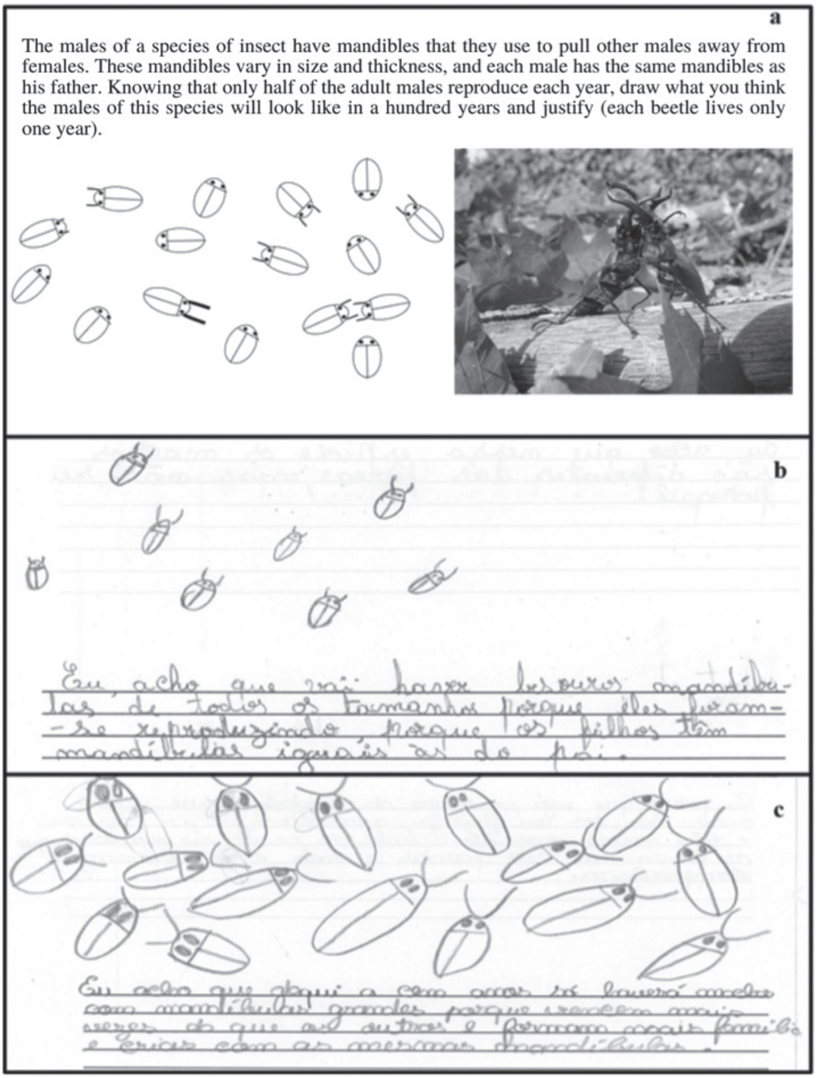
Category of analysis	Definition	Example of an answer classified as evidence for a category
Trait relative frequency change	the student predicts that the expected fittest phenotype would become the most frequent	*I think that* ***in one hundred years there will be only males with big mandibles,*** *as these win more often than the others and form more families and have more offspring with the same mandibles*
Selective advantage	the student states that the expected fittest males would win more fights	*I think that in one hundred years there will be only* ***males with big mandibles, as these win more often than the others*** *and form more families and have more offspring with the same mandibles*
Differential reproduction	the student justifies the frequency increase of the expected fittest male phenotype mentioning its differential reproduction advantage.	*I think that in one hundred years there will be only males with big mandibles, as these win more often than the others and* ***form more families and have more offspring with the same mandibles***
Differential survival	the student justifies the frequency increase of the expected fittest male phenotype mentioning its differential survival advantage.	*Because the* ***males with small beaks die more often in the fights.***

A score of one was attributed to each category except differential survival, as sexual selection does not require differential survival to take place. The level of understanding of evolution by sexual selection (LUESS) revealed by each answer, regarding both predictions and corresponding justifications, was determined by summing the scores attributed to each rubric item identified in that answer. The LUESS could range between L0: no evolutionary thinking involved in the answer (see example in Figure 1b), to L3: the ability to correctly predict population evolution and justify it with differential reproduction due to differential ability to win fights (Figure 1c).

Two science education researchers evaluated all of the students' answers: one with a background in primary school teacher training (AP), and one with an evolutionary biology background (XSP). Given the evaluators' training, interrater reliability was estimated as the percentage of initial agreement between the evaluators (McHugh, 2012). Interrater reliability was higher than 94.8% for all of the items analysed, a reliability considered as acceptable (Stemler, 2004, p.3). Answers not equally rated by the two researchers were discussed and, failing a consensus, removed from the analyses. The McNemar test was used to estimate the statistical significance of the changes in the frequency of each coding rubric item and the Wilcoxon test was used to estimate the statistical significance of students' LUESS between pre- and post-tests. All of the statistical analyses were performed with SPSSv23.

Figure 1

Test presented to the students before and after the intervention and (a) example of students' answers classified as L0 (b) and L3 (c)



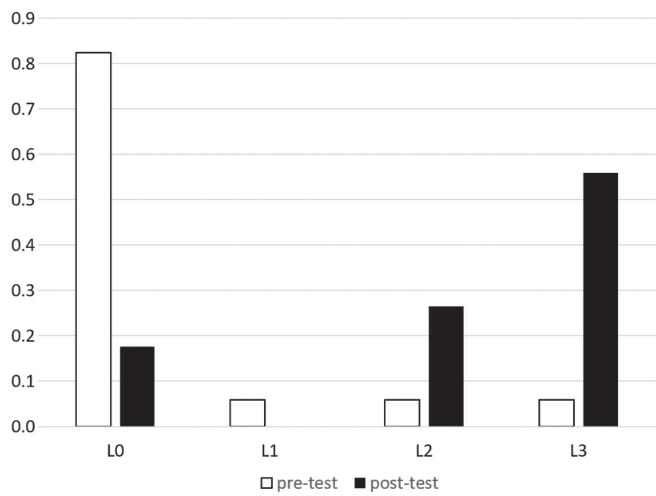
Translation of the student's answer in b) »I think that there will be beetles of all mandible sizes because these reproduced and the mandibles of the sons are similar to those of their fathers«. Translation of the student's answer in c) »I think that in one hundred years there will be only males with big mandibles as these win more often than the others and form more families and have more offspring with the same mandibles«. Photo in a) reproduced under the creative commons share alike license from Von Anaxibia H. Rothacher. Original upload was de: User: Matthias1987 - {own} http://h-r.gmxhome.de/index.htmltransfered from de:Datei:Lucanus cervus73.jpg, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=8768963.

Results

Table 2 shows the relative frequency of the answers that were assigned to each category of analysis (examples of answers can be found in Figure 1). When the two target classes are considered, more than 82% of the students revealed an L0 of the LUESS in the pre-tests. After engaging in the educational activities, 56% of the students achieved L3 of the LUESS (Figure 2). Thus, there was a significant increase in the target classes' LUESS in the post-tests (Table 2) in both classes.

Figure 2

Frequency of students attributed to each level of understanding of evolution by sexual selection (LUESS) when the two target classes are considered in both pre- and post-tests



The increase in students' LUESS from the pre-test to the post-test was due to a significant increase in the proportion of students who i) predicted that the expected fittest phenotype would become the most frequent and justified this prediction by ii) the increased ability of individuals with longer mandibles to win fights (selective advantage, Table 2), which would result in iii) an increased chance to secure females and have more progeny (differential reproduction; Table 2). No significant increase was observed in the frequency of students mentioning differential survival of the two phenotypes in any of the classes.

Table 2

Results of pre- and post-tests evaluating the students' ability to apply sexual selection to predict biological scenarios

Classes	Tests	% of students' answers including the analysed criteria				
		Trait relative frequency *change*	*Differential reproduction*	*Selective advantage*	*Differential survival*	*Average LUESS*
K3T N = 19	Pre	10.5	5.3	5.3	0.0	0.21
	Post	84.2	78.9	63.2	10.5	2.26
	Dif.	**73.7 (p = 0.001)**	**73.7 (p = 0.000)**	**57.9 (p = 0.003)**	10.5 (p = 0.500)	**2.05 (Wp < 0.001)**
K3C N = 12	Pre	50.0	0.0	9.1	10.0	0.55
	Post	41.7	0.0	8.3	25.0	0.50
	Dif.	-8.3 (p = 1.000)	0.0	-0.8 (p=1.000)	10.0 (p = 1.000)	0.05 (Wp = 0.317)
K4T N = 15	Pre	26.7	13.3	13.3	0.0	0.53
	Post	80.0	60.0	73.3	0.0	2.13
	Dif.	**53.3 (p = 0.008)**	**46.7 (p = 0.039)**	**60.0 (p = 0.004)**	0.0	**1.6 (Wp = 0.004)**
K4C N = 12	Pre	0.0	0.0	0.0	0.0	0
	Post	8.3	8.3	0.0	0.0	0.17
	Dif.	8.3 (p = 1.000)	8.3 (p = 1.000)	0.0	0.0	0.17 (Wp = 0.317)

Note. K3T – Target third-grade class; K3C – Control third-grade class; K4T – Target fourth-grade class; K4C – Control fourth-grade class; N – sample size; Dif. – difference between results obtained in the pre-test (Pre) and the post-test (Post) by the same students; p – p values obtained in McNemar tests; Wp – p values obtained in Wilcoxon tests. All statically significant differences are highlighted in bold.

Discussion

The results from the present study support the hypothesis that students in third- and fourth-grade classes can learn about sexual selection when they engage in activities that model sexual selection by mate choice and intrasexual competition. This is supported by the strong and significant increase in the students' LUESS from the pre-test to the post-test in the two target classes (Figure 2). The students were shown to learn about the key concepts related to sexual selection: selective advantage, differential reproduction and trait relative frequency change. Although students have already been shown to be capable of learning about natural selection (Brown et al., 2020; Campos & Sá-Pinto, 2013; Emmons et al., 2017; Kelemen et al., 2014; Sá-Pinto et al., 2021a), to our knowledge, this is the first study analysing the ability of primary school students to learn about sexual selection. Although sexual selection has been given much less attention in evolution education than natural selection, this evolutionary process strongly impacts species' evolution and speciation processes. It therefore allows students to understand patterns of sexual dimorphism and the persistence of some features related to reproduction that may decrease individuals' survival, such as the tail of the peacock (reviewed in Sá-Pinto et al., 2017b). The results of the present study also support the potential of exploring sexual selection in order for students to learn about the role of differential reproduction, which is a key concept for the understanding of evolution that has been shown to be difficult for primary school students (Sá-Pinto et al., 2017a; Sá-Pinto et al., 2021a). In fact, after engaging in the educational activities, 60% and 78.9% of the students in the fourth- and third-grade classes, respectively, correctly applied the concept of differential reproduction to justify their prediction. This strongly contrasts with results reported in studies where students were engaged in activities exploring natural selection. After engaging in a storytelling activity and in a transdisciplinary project-based learning activity about natural selection, only 32% and 25% of the students, respectively, applied the concept of differential reproduction to explain or justify the predictions made about biological scenarios (Brown et al., 2020; Sá-Pinto et al., 2021a). The differences observed between the latter studies and the present one suggest that activities exploring sexual selection may contribute more effectively to students' understanding of the importance of differential reproduction than activities exploring natural selection. However, the different studies were performed with distinct students, by distinct people, using distinct educational approaches and in distinct cultural backgrounds, thus precluding a direct comparison between them. The ability to compare the results is further limited by the low number of students involved in the three studies. Furthermore, the time between the activities and the post-tests was shorter in the present study than in the previous ones, which may have impacted students' outcomes. Accordingly, additional studies are needed to comparatively evaluate the impact of activities exploring sexual and natural selection on students' learning about differential reproduction.

An alternative explanation for the differences observed in the use of the concept of differential reproduction in the present and previous studies may lie in the different biological scenarios presented in the evaluation instruments used, which may have caused students to mobilise the concept of differential reproduction differently. In fact, the test used in this study presents a single biological scenario (trait gain in animals), precluding observation of whether the effects reported here are context-dependent, as it has been shown to occur in other situations (Nehm, 2018). Furthermore, this test presents the students with a very simplified model of what happens in the real species in terms of genetic diversity, heredity and trait expression. Additional studies exposing students to evaluation instruments with distinct and more realistic scenarios of natural and sexual selection would be needed to understand how the biological scenarios used impacted the mobilisation of the concept of differential reproduction.

We should also highlight the fact that the model we implemented in this activity mostly explored the effects of biased sex ratios in evolution by sexual selection, without providing any reason for the observed sex bias. However, several studies have shown that, with the exception of a small number of species, biased sex ratios do not explain the patterns of sexual selection observed (Andersson et al., 1994). In fact, operational sex ratios and Bateman's principles better explain the patterns of the observed sexual selection (Andersson et al., 1994; Jones et al., 2005). Accordingly, future studies could explore how students learn about the factors driving sexual selection and focus on the reasons for biased operational sex ratios. For older students, Bateman's principles may also be explored to promote a deeper understanding of the causes of sexual selection. Future studies should also analyse whether the activity reported here results in students' misconceptions about natural populations' sex ratios or whether it fosters teleological explanations.

In any case, our results support the importance of exploring sexual selection during mandatory education and from the initial school years, as well as the importance of introducing this concept in curricula and textbooks. The Portuguese official standards and the next generation science standards from the United States of America do not explicitly mention sexual selection, although some of the learning goals detailed allow or even require this concept to be explored (reviewed in Sá-Pinto et al., 2017b). A better picture of how this concept is explored is hampered by the lack of comprehensive comparisons of curricula of different countries in terms of their evolution concepts (Sá-Pinto et al., 2021b). Regarding textbooks, Cavadas (2017) has shown that sexual selection was historically covered by Portuguese seventh-grade textbooks from 1890 to 1955, but no information is available on how this concept is present in today's textbooks, thus suggesting the importance of analysing recent textbooks. However, textbooks have also been reported to display important misconceptions on evolution (Cavadas, 2017; Nehm et al., 2008; Prinou et al., 2011) and a lack of concepts such as the Nature of Science (Kapsala et al., 2022), which are considered important for evolution understanding (Sá-Pinto et al., 2021b). Another important aspect to consider for introducing natural and sexual selection in primary schools is teacher training, as several studies report low pedagogical content knowledge and low willingness to teach evolution (Cavadas & Sá-Pinto et al., 2021; Prinou et al., 2011), as well as other topics of biology (see, for example, Yli-Panula et al., 2017), among many primary school teachers.

Conclusion

In the present study, we show that there is a positive impact of the early introduction to evolution by sexual selection to students. Our results support the importance of developing and testing active learning activities that allow students to learn about this process from the first school years, with increasing complexity. In fact, when compared to natural selection, much fewer activities have been described for students to learn about sexual selection (and even fewer have been studied for their impacts on student knowledge; however, see Bouwma-Gearhart & Bouwma, 2015; Fee & Alfano, 2013; Lawson, 2003; Moore et al., 2012; Sá-Pinto et al., 2017b). The study also supports the importance of explicitly introducing this concept in national curricula in order to promote a deeper understanding of evolutionary processes and the impacts of these processes on our own features and on daily life problems.

The present study has some limitations that should be taken into consideration and that highlight the importance of performing additional studies: i) the limited number of students, school contexts and countries do not allow us to generalise our results; ii) the post-test was done one day after the students explored the last activity, thus precluding an understanding of the long-term learning impacts of the activity; iii) the test used presents students a single biological scenario (trait gain in animals), thus precluding gaining an insight into whether the effects reported here are context-dependent, as has been shown to be the case in other situations (Nehm, 2018). Accordingly, there is a need for studies that involve a higher number of students and school contexts, that include an additional post-test performed to study the long-term learning effects of the educational programme, and that use tests with at least one additional biological scenario that would result in trait loss.

The present study should be taken as an initial step to understand the impact of introducing primary school students to sexual selection in their understanding of evolution. The results support suggestions previously made by several authors and institutions (Nadelson et al., 2009; NRC, 2012, 2013; Wagler, 2010, 2012) that students should explore evolutionary processes from the first school years in order to foster their evolution understanding.

Acknowledgements

We would like to acknowledge the teachers and the students who participated in this study, along with their parents and the school board team. Patrícia Pessoa and Xana Sá-Pinto are funded by Portuguese national funds through FCT – Fundação para a Ciência e a Tecnologia, I. P., within the scope of the PhD grant 2020.05634.BD, and of the framework contract foreseen in the numbers 4, 5 and 6 of Article 23 of the Decree-Law 57/2016 of 29 August, amended by Law 57/2017 of 19 July, respectively. This work is financially supported by National Funds through FCT – Fundação para a Ciência e a Tecnologia, I. P., under the project UIDB/00194/2020. The inED is funded by National Funds through the FCT – Fundação para a Ciência e a Tecnologia, I. P., within the scope of the project UIDB/05198/2020 (Centre for Research and Innovation in Education, inED).

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