Baytelman, Andreani; Loizou, Theonitsa; Hadjiconstantinou, Salomi

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Relationships between Epistemological Beliefs and Conceptual Understanding of Evolution by Natural Selection

Andreani Baytelman*[1], Theonitsa Loizou[2] and Salomi Hadjiconstantinou[3]

This study researches relationships between 12th-grade students' epistemological beliefs towards science and their conceptual understanding of evolution by natural selection. Forty-two 12th-grade students in a suburban high school in Cyprus, who participated in a biology course, completed measures of their: (a) epistemological beliefs towards science before the intervention of being taught evolution (b) conceptual understanding of evolution by natural selection after evolution intervention, (c) epistemological beliefs towards science after evolution intervention. Based on previous research, we hypothesised there would be a significant relationship between students' epistemological beliefs and their conceptual understanding of evolution by natural selection after the evolution intervention. We also hypothesised that inquiry-based intervention on evolution by natural selection would foster students' epistemological beliefs. Our results indicate that participants' initial epistemological beliefs predict very modestly and statistically non-significant learning achievements on conceptual understanding of evolution by natural selection. However, our results show a significant improvement in participants' epistemological beliefs after engagement in an inquiry-based intervention on evolution by natural selection. The educational significance of this and its implications are discussed.

Keywords: conceptual understanding; epistemological beliefs; evolution by natural selection; inquiry-based teaching and learning, students

1 *Corresponding Author. Department of Education at University of Cyprus, Cyprus; baytel@ucy.ac.cy.
2 Lykeio Paralimniou, Cyprus.
3 Paralimni high school, Famagusta, Cyprus.

Razmerja med epistemološkimi verjetji in pojmovnim razumevanjem evolucije z naravno selekcijo

Andreani Baytelman, Theonitsa Loizou in Salomi Hadjiconstantinou

Študija se usmerja na odnose med epistemološkimi verjetji srednješolcev 12. razreda do znanosti in njihovim pojmovnim razumevanjem evolucije z naravno selekcijo. 42 srednješolcev 12. razreda primestne srednje šole na Cipru, ki so sodelovali pri pouku biologije, je opravilo meritve: a) epistemoloških verjetij do znanosti pred predstavitvijo evolucije; b) pojmovnega razumevanja evolucije z naravno selekcijo po intervenciji evolucije; c) epistemološka verjetja do znanosti po intervenciji evolucije. Na podlagi prejšnjih raziskav smo domnevali, da obstaja pomembna povezava med epistemološkimi verjetji srednješolcev in njihovim pojmovnim razumevanjem evolucije z naravno selekcijo po vpeljavi evolucije. Prav tako smo predpostavljali, da bi tovrstna intervencija na temo evolucije z naravno selekcijo, ki temelji na raziskovanju, spodbudila epistemološka verjetja srednješolcev. Izsledki kažejo, da izhodiščna epistemološka verjetja udeležencev napovedujejo zanemarljive in statistično nepomembne učne dosežke o pojmovnem razumevanju evolucije z naravno selekcijo, vendar pa naši izsledki dokazujejo znatno izboljšanje epistemoloških prepričanj udeležencev po izvedeni intervenciji, ki temelji na raziskavah o evoluciji z naravno selekcijo. Nazadnje se v prispevku razpravlja o izobraževalnem pomenu omenjenega in pripadajočih posledicah.

Ključne besede: pojmovno razumevanje, epistemološka verjetja, evolucija z naravno selekcijo, poučevanje in učenje na podlagi poizvedovanja, srednješolci

Introduction

Evolution by natural selection is the central and overarching theory in biology. Educating students about evolution by natural selection is vitally important because it is one of the most consistent and unifying theories, capable of explaining a large number of natural phenomena at different levels (Dobzhansky, 1973; National Research Council (NRC), 2012). While in everyday conversations, the term 'theory' often indicates the absence of data and well-supported explanations, in science, a theory, according to the US National Academy of Science (NAS), 'is a wellsubstantiated [sic] explanation of some aspect of the natural world that can incorporate facts, laws, inferences and tested hypotheses'. In this sense, evolution by natural selection is a scientific theory, representing a sophisticated body of explanations for the fact of evolution (Gregory, 2008; NAS, 1984, p. 15; NAS, 2008, p. 53).

Natural selection is a key mechanism of evolution and is responsible for the evolution of adaptive features. Without an understanding of natural selection, it is impossible to explain how or why living organisms that exist on the earth have come to exhibit their wide diversity and complexity. An understanding of natural selection also is getting more and more important in other contexts, including agriculture, resource management and medicine. In particular, evolution by natural selection improves our understanding of various public health issues such as vaccinations, epidemiology, and antibiotic resistance, biological impacts of climate change, ecological issues such as invasive species, and other environmental impacts of human activity such as climate change and pesticide resistance, as well as food security and similar issues. (Dunk & Wiles, 2018).

Despite the importance of the evolutionary theory by natural selection, it remains one of the most widely misunderstood concepts of contemporary science (Miller et al., 2006; To et al., 2017). In addition, although various scientific concepts present challenges for students, evolutionary theory by natural selection is considered to be particularly difficult to understand (Gregory, 2009) and is more likely to be rejected for religious, emotional, and ideological reasons than other scientific theories (Gregory, 2009). Several studies suggest that students, teachers, and the public have a variety of resistant misconceptions about evolution by natural selection (Baytelman, 2022; Harms & Reiss, 2019; Newbrand & Harms, 2017); sparse research and knowledge exist on educational approaches and teaching strategies that can effectively change the existing situation (Harms & Reiss, 2019).

Previous research suggests the association between students' epistemological beliefs and their understanding of evolutionary theory (Cho et al., 2011;

Kizilgunes et al., 2009; Sinatra et al., 2003). This indicates that the investigation of the interrelationship of epistemological beliefs and conceptual understanding of evolution is an important issue for research. However, existing research on students' epistemological beliefs and understanding of evolution by natural selection is rare, and the results are inconclusive (Athanasiou & Papadopoulou, 2015; Borgerding et al., 2017; Deniz et al., 2008; Sinatra et al., 2003; Southerland et al., 2001; Southerland et al., 2005;). That means that more research is needed in this field (To et al., 2017).

Our aim in this study is to explore the relationships between 12th-grade students' epistemological beliefs and conceptual understanding of evolution by natural selection. To this end, answers to the following research questions were sought:

1. What are the 12th-grade students' epistemological beliefs before and after inquiry-based intervention on evolution?
2. To what extent does inquiry-based intervention on evolution improve 12th-grade students' epistemological beliefs?
3. To what extent do 12th-grade students' initial epistemological beliefs predict their learning achievements regarding the conceptual understanding of evolution by natural selection after inquiry-based intervention?

By doing this, we hope to gain a better understanding of the relationships between epistemological beliefs and conceptual understanding of evolution by natural selection and contribute to the development of a relevant theoretical framework.

Evolution by natural selection and education

Evolution by natural selection is the unifying theme of all biology, through which living organisms and communities can be understood most clearly (Dobzhansky, 1973). This framework for the life sciences is reflected in the strong acceptance of evolutionary theory amongst biologists (AIBS, 1994, p.29; Lynn et al., 2017). However, acceptance of evolution is not nearly as universal amongst members of the general public as it is in the scientific community (Branch & Scott, 2008; Miller et al., 2006; Rosengren et al., 2012).

Furthermore, several studies indicate that evolution by natural selection remains poorly understood by students (Greene, 1990; Nehm & Reilly, 2007; Nehm et al., 2009; Shtulman, 2006; Spindler & Doherty, 2009), science teachers (Baytelman, 2022; Nehm et al., 2009), and the general public (Evans et al., 2010). This lack of understanding has been attributed to diverse cognitive, epistemological, emotional, and religious factors (Reiss, 2018; Rosengren et al., 2012).

At the core of many of these misunderstandings is a teleological concept in students' reasoning about natural selection. In general, teleological thinking is the assumption that things happen for a reason. According to Kampourakis:

> […] on the one hand, teleological explanations can be based on intentional design, that is, one can state that a feature exists because it was intentionally created for a purpose. On the other hand, teleological explanations can be based on functionality, that is, one can state that a feature exists in order to perform a function that is useful for the whole to which this feature belongs. (2020, p.3)

Several studies have shown that students believe that living organisms have the traits that they currently possess because those traits perform functions that aid survival (Jensen & Finley, 1995; Pedersen & Halldén, 1994; Tamir & Zohar, 1991).

Another conceptual bias is anthropomorphism, meaning to attribute human reasoning to non-human beings (Tamir & Zohar, 1991). Studies suggest that anthropomorphism is positively related to teleological beliefs about biological phenomena and facilitates them (Kelemen & Diyanni, 2005; Kelemen et al., 2013). Yet, as suggested by Gregory (2009), anthropomorphism is intimately tied to the misconception that individual organisms evolve in response to challenges imposed by the environment rather than recognising evolution as a population-level process.

Additional student misconceptions about the theory of evolution by natural selection include the following: organisms change because of the use or disuse of organs or because acquired traits can be transmitted to offspring (Kampourakis & Zogza, 2008); organisms change because of need (Shtulman, 2006; Sinatra et al., 2003; Sinatra et al., 2008); all mutations are harmful (Nehm & Reilly, 2007); sources other than mutations and recombinations are responsible for genetic diversity (Hallden, 1988); humans are not subject to evolution (Sinatra et al., 2003). These misconceptions are often very resistant to learning about evolution (Ferrari & Chi, 1998; Gregory, 2009; Jensen & Finley, 1995; Kampourakis & Zogza, 2008; Nehm & Reilly, 2007; Spindler & Doherty, 2009). This knowledge about evolution misconceptions is an invaluable resource for further research on evolution education in order to address students' misconceptions and foster their conceptual understanding.

Moreover, biology teachers also have problems understanding evolution-related topics (Baytelman, 2022; Reiss, 2018; Sinatra et al., 2003; Yates &

Marek, 2014). Evidence suggests that the lack of subject content knowledge by biology teachers can be a reason for the development of students' misconceptions about evolution and poorer knowledge after teaching it than before (Yates & Marek, 2014). In addition, teachers face many challenges in engaging students in designing and carrying out investigations and analysing data about evolutionary processes in the classroom. One such challenge is the long timescales for evolution to occur in most species. In particular, since evolution takes place over long periods and the geological notion of 'deep time' is one that is difficult to understand and teach, it forms one of the major cognitive difficulties that students have in learning about evolution by natural selection (Reiss, 2018). Other challenges include the fact that observing changes in populations does not necessarily help students to understand the mechanisms of evolution by natural selection (Sinatra et al., 2003). Technically demanding and cost-prohibitive materials are further challenges (Sinatra et al., 2003).

Students' Epistemological beliefs

Epistemology is 'an area of philosophy concerned with the nature and justification of human knowledge' (Hofer & Pintrich, 1997, p. 88). Epistemological beliefs refer to individuals' beliefs about the nature of knowledge and the nature of knowing (Baytelman et al., 2020a; Greene et al., 2016; Hofer & Pintrich, 1997; Muis et al., 2015; Schiefer et al., 2022; Sinatra et al., 2003).

Researchers in the field of epistemology have proposed a variety of models for conceptualising and examining epistemological beliefs (Baytelman et al., 2020a). Early studies focused on the way in which epistemological beliefs developed. Perry (1970) proposed a model that described nine levels in epistemological beliefs, ranging from the belief that knowledge is objective to the belief that knowledge is radically subjective, and finally, to the belief that knowledge has objective and subjective aspects. This type of model represents a developmental model of epistemological beliefs (Baytelman et al., 2016a, 2020a; Kuhn, 1991, 2001; Kuhn et al., 2000; Scheifer et al., 2022). Based on Perry's model, Kuhn and her colleagues (2000) developed a framework for the development of epistemological beliefs, describing different stages: realist, absolutist, multiplist, and evaluativist (Kuhn et al., 2000, p. 311; Scheifer et al., 2022).

Specifically, Kuhn and her colleagues (2000, p. 311) suggested that preschoolers can be described as realists but already show some epistemological awareness (assuming that assertions are copies of external reality; reality is directly knowable and knowledge comes from an external source and is certain) Children at the elementary school level are described as absolutists (assuming that assertions are correct and incorrect in their representation of reality, it is directly knowable and, knowledge is absolute, certain, non-problematic, right or wrong). Between middle and late childhood, students can be described as multiplistic (assuming that assertions are opinions freely chosen, reality is not directly knowable, and knowledge is generated by humans, is uncertain and might be considered as opinion). The later level of epistemological understanding is the evaluativist level, achieved usually in adulthood. Evaluativists reintegrate the objective dimension of knowing by acknowledging uncertainty without forsaking evaluation (assuming that assertions are judgments that can be evaluated, reality is not directly knowable, and knowledge is generated by humans and is uncertain) (Kuhn et al., 2000; Scheifer et al., 2022). They believe that there are 'shared norms of inquiry and knowing, and some positions may be reasonably more supported and sustainable than others' (Mason, 2016, p. 376).

Later studies showed epistemological beliefs to be multi-dimensional (Hofer, 2016; Schommer, 1990; Schommer et al., 1992; Schommer-Aikins, 2004), proposing a dimensional model. Although there is consensus on the existence of multiple more-or-less independent dimensions of epistemological beliefs (Hofer, 2016), a debate about the specific dimensions of the construct has evolved (Baytelman et al., 2016a, 2016b, 2020a, 2022). Schommer (1990) proposed that epistemological beliefs should be described as a system of basically independent beliefs (epistemological dimensions), conceptualised as beliefs about the simplicity (related to the structure of knowledge), certainty (related with the stability of knowledge), and source of knowledge, as well as beliefs about the speed and ability of knowledge acquisition (Baytelman et al., 2020a; 2022) While the dimensions of simplicity, certainty, and source in Schommer's conceptualisation fall under the more generally accepted definition of epistemological beliefs (known as beliefs about the nature of knowledge (simplicity, certainty) and knowing (source) (Hofer & Pintrich, 1997; Hofer, 2016)) the speed and ability dimensions are controversial because they mainly concern beliefs about learning (speed) and intelligence (ability) (Baytelman et al., 2020a; 2022).

As suggested by Hofer and Pintrich (1997), epistemological beliefs should be defined with two dimensions regarding the nature of knowledge and two dimensions concerning the nature of knowing. The two dimensions concerning the nature of knowledge (what one believes knowledge is) are (i) Simplicity of Knowledge, ranging from the belief that knowledge consists of an accumulation of more or less isolated facts to the belief that knowledge consists of highly interrelated concepts; and (ii) Certainty of Knowledge, ranging from the belief that knowledge is absolute and unchanging, to the belief that knowledge is tentative and evolving). The two dimensions regarding the nature of knowing (how one comes to know) are (iii) Source of Knowledge, ranging from the conception that knowledge originates outside the self and resides in external authority from which it may be transmitted to the conception that knowledge is actively constructed by the person in interaction with others; and (iv) Justification for Knowing, ranging from the justification of knowledge claims through observation and authority or on the basis of what feels right, to the use of rules of inquiry and the evaluation and integration of different sources (Baytelman et al., 2016a; 2016b; 2020a; 2022).

In addition, Conley and her colleagues (2004) proposed a new epistemological dimension under the dimensions concerning the nature of knowledge, which they named 'Development of Knowledge'. Although the developmental and multidimensional models have various differences, according to Pinitrich, (2002, p. 400), 'the fairly well-established trend is that individuals move from some more objectivist perspective through a relativistic one, to a more balanced and reasoned perspective on the objectivist–relativistic continuum, with this latter position reflecting a more sophisticated manner of thinking' (Baytelman et al., 2020a, 2022).

Later, epistemological beliefs were examined for their impact on learning (Schommer, 1990). Researchers have reported that epistemological beliefs are related to academic performance, comprehension, conceptual change and conceptual understanding, views of science, innate learning and choosing science as a career, conceptions of teaching, self-efficacy beliefs, students' motivation, and higher levels of self-concept and self-efficacy (Chen, 2012; Cheng et al., 2009; Mason et al., 2013; Trevors et al., 2017). Additionally, studies argue that students' epistemological beliefs have a direct impact on the selection of learning strategies or approaches, the process of shaping conceptions and problem-solving (Chan et al., 2011) and the individual's ability to generate alternative arguments and counterarguments (Baytelman et al., 2020a).

Given the great importance of epistemological beliefs in education, various attempts have been made to foster students' epistemological beliefs at different levels of education (Muis et al., 2016; Schiefer et al., 2020; Baytelman et al., 2020a, 2022). Since the multidimensional model concerning epistemological beliefs is a system of more or less independent epistemological dimensions, which are not necessarily developing in synchrony with each other (Baytelman et al., 2020a; Muis et al., 2015), it is important to make efforts to foster all dimensions of students' epistemological beliefs, using a variety of didactical approaches.

To promote students' epistemological beliefs, science educators have developed and implemented a range of didactical approaches to provide extra support for them (NRC, 2012). Inquiry-based learning (Shi et al., 2020) refers to the active learning processes in which students are inevitably engaged (Minner et al., 2010); inquiry-based teaching (Chinn & Malhotra, 2002; Shi et al., 2020) refers to the teacher's role concerning students' learning: a shift from 'dispenser of knowledge' to facilitator or coach for supporting students' learning (Anderson, 2002), dialogic argumentative activities, reflective judgment through socioscientific issues (Zeidler et al., 2009) and using the history of science (Matthews, 1992, 1994) are some of the recommended didactical approaches.

In particular, the term 'inquiry-based learning' refers to the engagement of students in active learning processes during which they ask questions about a particular domain, identify the problem, search for information, generate testable hypotheses, plan methods, collect evidence, analyse data, draw conclusions, and communicate them (Pedaste et al., 2015; Sandoval, 2004). In such a learning process, the teacher becomes a facilitator and guide, challenging students to think beyond their current processes by offering guided questions, scaffolding, and reflection opportunities (Anderson, 2002). Researchers reported that classroom inquiry can foster students' conceptual understanding of scientific concepts and phenomena (Schröder et al., 2007), higher-order thinking skills, such as critical thinking (Haury, 1993), investigation skills (Minner et al., 2010; Sandoval, 2004) modelling and argumentation skills (Beernärt et al., 2015), as well as communication and cooperation skills (Anderson, 2002; Minner et al., 2010) Additionally, classroom inquiry can offer experiences with science, promote the development of an epistemological awareness of how science operates (Chinn & Malhotra, 2002) and develop positive attitudes towards science (Shymansky et al., 1983).

Concerning epistemological beliefs, students engaging in inquiry-based learning activities can understand that (i) scientific knowledge is constructed by people and not simply discovered, (ii) scientific knowledge is socially constructed, (iii) scientific methods are diverse depending on scientific disciplines but rely on scientific standards (iv) scientific knowledge is tentative and can change as new observations, hypotheses, and ideas come to light (Sandoval, 2005). Such understanding about scientific knowledge, as well as reflection and explicit epistemological discourse, can improve students' epistemological beliefs (Sandoval & Morisson, 2003; Sandoval & Reiser, 2004; Sandoval, 2005, 2014).

Furthermore, engagement in dialogic argumentative activities may support the development of students' awareness of the complexity, source, and justification of scientific knowledge (Iordanou, 2016). In addition, the utilisation of the history of science instructional approach might facilitate students' understanding of the tentative and uncertain nature of scientific knowledge and how scientific knowledge is developed and created (Matthews, 1994). However, the recommended didactical approaches are synergistic, built upon one another, and provide opportunities for fostering students' epistemological beliefs.

Epistemological beliefs and conceptual understanding of evolution

Studies on students' epistemological beliefs and understanding of biological evolution by natural selection are very rare, and the results are inconclusive (Borgerding et al., 2017; Deniz et al., 2008; Sinatra et al.; 2003; Southerland et al., 2001; Southerland et al., 2005; To, et al., 2017).

Data from Sinatra and her colleagues (2003) suggested an association between epistemological beliefs, particularly beliefs about the tentative nature of knowledge and acceptance in human evolution, but they found no significant relationship between epistemological beliefs and understanding of evolution. Moreover, Deniz and his colleaques (2008) found no significant positive correlation between epistemological beliefs and an understanding of evolutionary theory. In contrast, Cho et al. (2011), investigating the role of epistemological beliefs on students' conceptual change in the learning of evolutionary theory, found a positive relationship between students‘ epistemological beliefs, particularly beliefs about the certainty and source of knowledge, and their conceptual change in the learning of evolution.

In the present work, we aim to gain a deeper understanding of the relationships between epistemological beliefs and conceptual understanding of evolution by natural selection.

Method

Participants

Forty-two (42) secondary school students participated in the study. They were 12^{th}-grade students, 17.5 years old (SD = 0.5); 26 of them were girls, and 15 were boys. The school was a suburban high school in Cyprus. The participants were Caucasian native speakers of Cyprus and shared the Greek language and a homogeneous middle-class social background. Students participated in the study as part of their biology classes (elective course), taught by their biology school teachers, who received specific training for evolution teaching from the Cyprus Ministry of Education and the University of Cyprus. Both biology school teachers had a master's degree and more than 15 years of experience. The students were taught biology in Grade 7 (two 45-minute class periods per week), in Grade 8 (one 45-minute class period per week), in Grade 9 (two 45-minute class periods per week), in Grade 10 (one 45-minute class period per week), and in Grade 11 (four 45-minute class periods per week- elective course). However, according to the Cyprus National Curriculum, they did not have any lessons on biological evolution before Grade 12.

All materials and assessment tools that were used for this study were in the Greek language.

Instructional Material

In the revised National Curriculum for Biology in Cyprus, 12^{th}-grade students are introduced to the topic of evolution by natural selection in Grade 12. Between Grades 7 and 11, students learn about biodiversity and inheritance, including the approach of reproduction, chromosomes, DNA, and genes. In particular, students learned about heredity as a genetic process, that differences between and within species can be interpreted as a result of differences in genetic information, and about the need to preserve biodiversity and protect endangered species (Cyprus Ministry of Education National Curriculum, 2021).

The unit on evolution by natural selection introduces 12^{th}-grade students to biological evolution by exploring the ideas proposed by different prominent naturalists before Charles Darwin, which were important for the development of evolutionary thought, and the ideas proposed by Darwin about evolution by natural selection. Specifically, at the introduction of the unit, teachers use a history of science approach, discussing with students the development of evolutionary thought, making mention of the ancient Greek philosophers Anaximander and Empedocles, the restraining influence of the church during the Middle Ages and the ideas of the prominent naturalists of the Enlightenment. Then, special mention is made to Lamarck's work and its contribution to later studies about biological evolution, as well as to the founder of the modern theory of evolution, Charles Darwin. The unit continues with inquiry-based learning activities to teach students the evidence for evolution from geology, anatomy, embryology, biogeography and molecular biology, as well as the adaptation of organisms to their environment. Furthermore, students learn that genetic mutation causing variation occurs at the gene level; monohybrid inheritance occurs when there are dominant and recessive alleles; sexual reproduction contributes to variation within a population; there are differences in genotypes or phenotypes between populations that inhabit different areas (geographic variation), the evolution of new species can be obtained over time through natural selection; genetic drift, gene flow, environmental factors contribute to biological evolution, phylogeny and human evolution, covering many generations.

For this study, the teaching intervention involved the implementation of a curriculum for evolution by natural selection, using the textbook entitled *Biology 12th* Grade Student Book: Evolution of Living Organisms, which not only covers the 12th-grade biology curriculum but extends it, specifically in relation to human evolution (Baytelman et al., 2020c). This textbook was developed by experienced biology educators, biology curriculum experts, and university biology professors. The teaching intervention took place over five 90-minute class periods, twice per week, in a total of 10 sessions.

The textbook is based on sequences of inquiry-based learning activities, which include adequate provisions for the identification of students' preconceptions and alternative ideas (misconceptions) on concepts related to evolution by natural selection. Additionally, the activities allow students to work collaboratively in a guided inquiry approach in order to investigate specific concepts and problems related to evolution by natural selection and obtain a deep conceptual understanding of the related mechanisms of evolution, epistemological understanding about different aspects of the nature of science, and thinking skills. In general, each activity has oriented questions on the topic that students are asked to investigate, as well as scientific information that students could use in order to formulate hypotheses, make predictions, obtain evidence, analyse data, create arguments, draw conclusions, and communicate their answers. The information is provided in the form of text, diagrams, models, infographics, historical reports, biographies, conceptual maps and geographical maps, among others. Teachers' competences for coordinating and facilitating inquiry-oriented learning processes are essential. The students work in groups (3–5 students), except for those activities that require individual work and reflection or those that require whole-class discussions.

The learning activities that stimulate the active engagement of students include hands-on learning and facilitate discussion, interaction, and reflection on the tasks. In general, the activities aim to develop students' conceptual understanding of evolution by natural selection, high-order thinking skills, such as critical and creative thinking, communication and collaboration skills and awareness of the nature of science. Further, the textbook includes different assessment tasks that can be applied for formative and summative purposes. Table 1 displays the activities presented in the textbook, which were used for the teaching intervention, by session.

Table 1

Activities presented in the textbook, by session

Session	Activity	Mobilising Skills
Sessions: 1-2	Introduction. Brief history of the development of evolutionary thought before Darwin, using a history of science approach. Darwin and his ideas about evolution. Evidence for evolution: Students study scientific information for collecting evidence for evolution from geology, anatomy and embryology, biogeography, and molecular biology, and constructing a concept map.	Epistemological awareness of the nature of science and how it operates Systematic observation skills Critical thinking skills Investigation skills, relying on different sources of evidence. Collecting and explaining relevant evidence. Communicating results. Communication, Collaboration skills.
Sessions: 3-4	Genetic and phenotypic diversity within and between populations. Students study scientific information for formulating hypotheses, making predictions, and carrying out investigation in order to obtain evidence and answer related questions related to genetic and phenotypic diversity. Examples of questions: How differences in skin colour among people are related to their adaptation and survival? What do dark-coloured mice have that allows them to have higher survival rates and leave a greater number of offspring than light-coloured mice?	Cognitive skills such as analysing data, creating a hypothesis and making predictions. Critical thinking and evaluative system thinking. Investigation skills relying on different sources of evidence. Collecting and explaining evidence. Analysing and drawing conclusions. Communicating results. Communication, Collaboration skills. Epistemological awareness of how science operates.
Sessions: 5-6	Mechanisms or phenomena responsible for genetic diversity in a population: Mutations, Sexual Reproduction, Random fertilisation, Random distribution of homologous chromosomes during metaphase of the 1st meiotic division, Random recombination of genes. Students study scientific information for formulating hypotheses, making predictions, and carrying out investigations in order to obtain evidence and answer related questions: Example of questions: Please explain: how the pathological gene that causes sickle cell anaemia which resulted from gene mutation is an adaptive advantage in areas with malaria? In people, 60% of the human olfactory genes are inactive, while in the mouse only 20%. Please explain the mechanism of the increase or decrease of the number of genes for a specific feature in a living organism.	Cognitive skills such as analysing data, creating hypotheses and making predictions. Critical thinking and evaluative system thinking, decision-making. Investigation skills relying on different sources of evidence. Collecting and explaining evidence Analysing and draw conclusions. Communicating results. Communication, Collaboration skills. Self-regulated learning skills. Epistemological awareness of how science operates.

Session	Activity	Mobilising Skills
Sessions: 7-8	Evolutionary Mechanisms: Natural Selection, Genetic drift (Bottlenecks and founder effects), Gene flow, Sexual selection. Students are engaged in authentic, problem-based learning activities, modelling procedures and 'hands-on' activities, discursive argumentation and communication with peers. Students use models to explain Natural selection, Bottlenecks and Founder effects and make predictions. Additionally, they use historical reports to explain the high incidence of carriers of inherited diseases in small communities in their own country (e.g., cystic fibrosis)	Critical thinking and evaluative system thinking, decision-making. Systematic observation skills. Modelling skills. Argumentation skills. Collecting and explaining evidence Analysing and draw conclusions. Communicating results. Communication, Collaboration skills. Self-regulated learning skills. Epistemological understanding of how science operates
Sessions: 9-10	Speciation, Phylogenetic trees, Human evolution. Students use Phylogenetic trees to illustrate and explain genetic relationships among different species of organisms and evolutionary relationships for organisms with a shared common ancestor. Additionally, they study and explain infographics related to morphological and behavioural characteristics of distinct Anthropidae, including humans.	Critical thinking and evaluative system thinking. Modelling skills. Argumentation skills. Explaining evidence, analysing and drawing conclusions. Communication, Collaboration skills. Epistemological understanding of how science operates. Self-regulated learning skills.

Instruments

Students' epistemological belief measures

To measure students' epistemological beliefs, we used the Dimensions of Epistemological Beliefs toward Science (DEBS) Instrument (Baytelman, 2015; Baytelman & Constantinou, 2016a; Baytelman et al., 2016b, 2020a, 2020b), which is based on the multidimensional perspective of epistemological beliefs. DEBS has been validated in the particular culture in which the research was conducted. The 30-item DEBS Instrument captures five epistemological dimensions: three dimensions related to the nature of knowledge (Certainty, Simplicity, and Development of Knowledge), and two dimensions related to the nature of knowing (Source and Justification of Knowledge). Each dimension of this instrument consists of six items rated on a four-point Likert scale with the following scoring options: strongly disagree=1, disagree=2, agree=3 and strongly agree=4. High scores on this measure represent more sophisticated epistemological beliefs, while low scores represent less sophisticated beliefs. The DEBS Instrument is suitable for high school and university undergraduate students. The 30-item DEBS Instrument is given in Appendix A.

Students' conceptual understanding of evolution measures

To assess participants' conceptual understanding of evolution by natural selection, we developed the *Conceptual Understanding of Evolutionary Theory Instrument* for this study using items of *The Knowledge About Evolution* (KAEVO) 2.0 instrument (Kuschmierz et al., 2020b) and new items according to the National Curriculum for evolutionary theory in Cyprus and the relevant textbook (Baytelman et al., 2020c). KAEVO 2.0 contains aspects of biological evolution that high school students are expected to know. The development of this questionnaire was based on a curriculum and textbook analysis to address content validity, and European experts in biology education and evolutionary biology reviewed the instrument (Kuschmierz et al., 2020b). It is considered to be an 'allrounder' among instruments measuring knowledge about evolution. Moreover, KAEVO 2.0 is suitable for various target groups (high school and university students in biology-related and non-biology-related fields of study; Kuschmierz et al., 2020b). All data and analyses are available in Kuschmierz et al. (2020b).

The *Conceptual Understanding Evolutionary of Theory Instrument* for this study consists of two parts with different answer formats: a) 5 multiple-choice questions, b) 1 matching question, c) 4 true/ false questions, d) 6 short-answer questions, and e) 3 open-ended questions. The instrument covers the concepts of adaptation, mutation, variation, inheritance, natural selection, sexual selection, genetic drift, gene flow, and phylogeny. Two experts of evolution by natural selection and two biology teachers reviewed the instrument for content validity. Sample items are given in Appendix B.

The multiple-choice questions, matching questions, and true/false questions were scored from 0 to 0.5. Three short-answer questions were scored from 0 to 1, and the other three short-answer questions were scored from 0 to 1.5 on the basis of their correctness. The open-ended questions were scored from 0 to 2 on the basis of their correctness and completeness by the first and second authors with Cohen's Kappa values k = .90. The possible maximum score of the instrument was 20.

For all questions, a zero score corresponds to a completely false answer. For the open-ended questions, a score of one (1) corresponds to a semi-correct or incomplete answer, and a score of two (2) corresponds to a fully correct and complete answer. No responses were treated as nonresponses and were excluded from the analysis.

Research procedure

This study was conducted in the second semester of the 2021/22 school year, from February to April 2022. The procedure of this study is described below.

1. Epistemological beliefs assessment before evolution teaching and learning intervention
   At the beginning of the second semester, before the evolution teaching and learning intervention, the biology teacher of each class administered the DEBS epistemological beliefs instrument (pre-test of epistemological beliefs). This lasted 20 minutes.
2. Evolution teaching and learning intervention
   From March to April, for five weeks, the evolution intervention took place. The intervention involved the implementation of a national curriculum about evolution. There were five (5) 90-minute class periods, twice per week, in the biology lab of the school.
3. Understanding Evolutionary Theory assessment after evolution intervention
   The *Conceptual Understanding of Evolutionary Theory Instrument* was administered one week after the end of the evolution intervention and lasted 30 min.
4. Epistemological beliefs assessment after evolution teaching and learning intervention
   One week after the administration of the *Conceptual Understanding of Evolutionary Theory Instrument*, the DEBS epistemological beliefs instrument was administered (post-test of epistemological beliefs) and lasted 20 min.

First, the means, standard deviations, minimum and maximum scores, and values of skewness and kurtosis of all variables of this study were calculated. Then, to investigate if the variables of the study were positively or negatively and significantly correlated among them, Pearson correlations were calculated.

To determine whether evolution by natural selection intervention improves 12th-grade students' epistemological beliefs, paired samples t-tests were carried out. To answer whether the 12th-grade students' initial epistemological beliefs can predict their learning achievements regarding their conceptual understanding of evolution by natural selection after the intervention, multiple regression analyses were carried out. This approach enables examining a relationship between a dependent variable (conceptual understanding of evolution by natural selection after instruction) and multiple independent variables (dimensions of epistemological beliefs). All participants completed the tasks in the same order. Two participants were excluded from the analysis because they did not complete all tasks.

Results

Table 2 displays the means, standard deviations, minimum and maximum scores, and values of skewness and kurtosis of all variables of this study. Participants' scores on the epistemological beliefs measure before evolution intervention suggested relatively sophisticated beliefs about the dimensions of nature of knowing (source and Justification of knowledge) and slightly less sophisticated beliefs about the dimensions of nature of knowledge (certainty, simplicity (structure of knowledge) and development of knowledge). Participants' scores on the epistemological beliefs measure after evolution intervention suggested relatively sophisticated beliefs about the dimensions of the source, justification, and development of knowledge and slightly less sophisticated beliefs about the dimensions of certainty and simplicity of knowledge. The more sophisticated epistemological beliefs before and after the evolution intervention were justification beliefs.

The measures of skewness and kurtosis indicated that all score distributions were approximately normal and thus appropriate for use in parametric statistical analyses.

Table 3 displays the Pearson correlations between all variables for epistemological beliefs before and after the evolution intervention and the conceptual understanding of evolution by natural selection. First, the Pearson correlation values indicated that the 12th-grade students' initial epistemological beliefs were not significantly correlated with their conceptual understanding scores about evolution after intervention (dependent variable).

Second, the Pearson correlations indicated asignificant positive correlation (Cohen, 1988, 1992) between simplicity beliefs (structure of knowledge) after evolution intervention and conceptual understanding of evolution by natural selection ($r=.35$, $p < .05$), indicating that more sophisticated epistemological beliefs about the structure of knowledge were correlated with high conceptual understanding scores on evolution by natural selection.

Third, the Pearson correlation measures showed that there was a statistically significant positive correlation between certainty beliefs after evolution intervention and conceptual understanding of evolution by natural selection ($r=.33$, $p < .05$), suggesting that more sophisticated epistemological beliefs about the certainty of knowledge were correlated with high conceptual understanding scores on evolution by natural selection.

To examine the 12^{th}-grade students' epistemological beliefs before and after inquiry-based teaching and learning intervention regarding evolution by natural selection, the measures of Table 2 were used. As illustrated in Table 2, participants' scores on the epistemological beliefs measure before the evolution intervention indicated relatively sophisticated beliefs about the nature of knowing (dimensions of source and justification of knowledge) and very slightly less sophisticated beliefs about the nature of knowledge (dimensions of certainty, simplicity and development of knowledge). Participants' scores on the epistemological beliefs measure after evolution intervention suggested relatively sophisticated beliefs about the dimensions of source, justification and development of knowledge and very slightly less sophisticated beliefs about certainty and the simplicity of knowledge. However, students held more sophisticated epistemological beliefs about the justification of knowledge before and after evolution intervention.

Table 2

Descriptive statistics for all variables related to the research questions (N = 40)

Variable	M		SD		Min		Max		Skewness (SE)		Kurtosis (SE)	
Conceptual understanding of evolution	14.61		4.79		6.00		20.00		-0.461(0.37)		-1.29 (0.73)	
Epistemological beliefs Dimensions	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test
Certainty of knowledge	2.57	2.63	0.38	0.48	1.50	2.00	3.16	3.50	-0.65(0.37)	0.43(0.37)	1.51 (0.73)	0.41(0.73)
Simplicity of knowledge	2.51	2.58	0.38	0.39	1.66	1.66	3.33	3.66	-0.23(0.37)	0.47(0.37)	-0.48 (0.73)	1.07(0.73)
Source of knowledge	2.74	2.94	0.49	0.47	2.00	1.50	3.66	4.00	0.46 (0.37)	-0.16(0.37)	-0.80 (0.73)	1.30(0.73)
Justification of Knowledge	2.88	3.07	0.37	0.37	2.16	2.50	4.00	3.66	0.56 (0.37)	0.01(0.37)	0.92 (0.73)	-1.32(0.73)
Development of knowledge	2.57	2.82	0.28	0.36	1.83	2.16	3.00	3.50	-0.95 (0.37)	0.46(0.37)	1.26 (0.73)	-1.29(0.73)

Table 3

Pearson correlations for all variables of the current study (N = 40)

	Variable	1	2	3	4	5	6	7	8	9	10	11
1.	Conceptual understanding of Evolution	-										
	Epistemological beliefs' dimensions											
2.	Certainty of knowledge Pre-test	0.23	-									
3.	Simplicity of knowledge Pre-test	0.23	0.10	-								
4.	Source of Knowledge Pre-test	0.12	0.26	0.17	-							
5.	Justification of Knowledge Pre-test	.031	0.22	0.11	0.16	-						
6.	Development of knowledge Pre-test	-0.04	0.29	0.30	-0.15	0.27	-					
7.	Certainty of knowledge Post-test	0.32*	0.49*	0.16	0.09	0.19	0.46**	-				
8.	Simplicity of knowledge Post-test	0.35*	0.07	0.19	-0.09	0.32*	0.20	0.28	-			
9.	Source of Knowledge Post-test	-0.29	0.22	0.03	0.42**	0.23	0.30	0.33*	-0.28	-		
10	Justification of Knowledge Post-test	0.10	0.13	0.33*	0.14	0.51**	0.23	0.23	0.13	0.27	-	
11	Development of knowledge Post-test	0.11	0.11	0.94	0.23	0.30	0.40*	0.35*	-0.01	0.40*	0.54**	-

Note. ***p < .001, **p < .01, two-tailed; *p < .05, two-tailed.

To investigate whether evolution by natural selection inquiry-based teaching and learning intervention improves 12th-grade students' epistemological beliefs, pre-and post-test scores were compared using paired samples test at 95% confidence. Table 4 displays Paired samples t-test results (α =0.05) comparing epistemological beliefs assessment scores before the evolution intervention with scores after the evolution intervention. The results indicated that all epistemological dimensions improved, but the source, justification, and development epistemological beliefs scores at the end of the semester, after the evolution intervention, were statistically significantly higher than the scores before the evolution intervention.

Table 4

Paired samples t-test results (α =0.05) comparing students' Epistemological beliefs before and after the evolution instruction.

Variable	M	SD	t(df)	Sig. (2-tailed)
Certainty of knowledge before evolution instruction	2.57	0.37	-0.52 (39)	0.60
Certainty of knowledge after evolution instruction	2.61	0.34		
Simplicity of knowledge before evolution instruction	2.51	0.38	-0.98 (39)	0.33
Simplicity of knowledge after evolution instruction	2.58	0.39		
Source of knowledge before evolution instruction	2.73	0.49	-2.41 (39)	0.02
Source of knowledge after evolution instruction	2.94	0.47		
Justification of knowledge before evolution instruction	2.88	0.37	-3.21 (39)	0.003
Justification of knowledge after evolution instruction	3.07	0.37		
Development of knowledge before evolution instruction	2.57	0.28	-4.44 (39)	0.00
Development of knowledge after evolution instruction	2.82	0.36		

To investigate, whether 12th-grade students' initial epistemological beliefs predict their learning achievements regarding the conceptual understanding of evolution by natural selection after inquiry-based teaching and learning instruction, multiple regression analysis was conducted using epistemological beliefs (epistemological dimensions according to the multidimensional perspective) as predictor variables.

The unstandardised regression coefficients (B) and intercept, the standardised regression coefficients (β), R^2, and adjusted R^2 after entry of all independent variables (IVs) are reported in Table 5.

Table 5

Results of linear regression analyses for variables predicting learning achievements regarding the conceptual understanding of evolution by natural selection after the intervention

Predictor variables **Initial epistemological beliefs** (before intervention)	**Conceptual understanding of evolution by natural selection** (after intervention)	
	B(SE)	β
Certainty of knowledge	3.96 (2.18)	0.31
Simplicity of knowledge	3.53 (2.11)	0.28
Source of knowledge	2.41 (1.64)	0.25
Justification of knowledge	0.80 (2.11)	0.06
Development of knowledge	-0.45 (3.07)	-0.26

Note. R = 0.42, R^2 = 0.17, Adjusted R^2 = 0.05

As illustrated in Table 5, with all IVs (Certainty, Simplicity, Source, Justification, and Development of Knowledge) in the equation, $R^2 = .17$, $F(5,34) = 1.37$, $p=.26$. The adjusted R^2 value of .17 indicates that 17% of the variability in the 12th-grade students' achievements of conceptual understanding of evolution by natural selection after teaching and learning intervention is predicted by their initial epistemological beliefs. That means that the initial epistemological beliefs contribute very modestly and non-significantly to that prediction.

Discussion and Conclusions

The aim of the present study was to investigate possible relationships between 12th-grade students' epistemological beliefs (epistemological dimensions) towards science and their conceptual understanding of evolution by natural selection. Regarding the relationship between epistemological beliefs and conceptual understanding of evolution by natural selection, our results indicate that the 12th-grade students' initial epistemological beliefs predict very modestly and statistically non-significantly their learning achievements on the conceptual understanding of evolution by natural selection after inquiry-based teaching and learning, measured via a specifically developed assessment tool.

In contrast, our results show a statistically significant improvement in some of the participants' epistemological beliefs (source, justification, and development of knowledge) after students' engagement in an inquiry-based intervention on evolution by natural selection. This finding of our study provides support to our hypothesis that inquiry-based intervention on evolution by natural selection would foster students' epistemological beliefs towards science. In addition, this result is consistent with previous findings reported in the literature (Shi et al., 2020) suggesting that inquiry-based teaching and learning is one recommended didactical approach for the promotion of epistemological beliefs.

Furthermore, the statistically significant improvement of students' source, justification, and development epistemological dimensions over the evolution intervention extends the literature in an important way, showing that engagement in inquiry-based teaching and learning activities on evolution by natural selection over an extended period of time can promote significant their epistemological beliefs. The opportunities provided in the context of the curriculum and in the textbook used for evolution teaching and learning intervention to articulate, explain, find relevant evidence, form arguments and counterarguments to convince peers, and reflect upon their own reasoning may have supported students to think deeper about the nature of the process through which knowledge develops (Greene et al., 2016; Hofer & Pintrich, 1997; Muis et al., 2015). The current research design does not enable us to identify exactly the mechanism that supported the epistemological gains observed, but our evidence indicates the contribution of guided inquiry-based teaching and learning activities to students' epistemological beliefs.

Moreover, our findings indicated a significant positive correlation between the simplicity beliefs dimension (beliefs that knowledge consists of highly interrelated concepts), after the evolution intervention, and conceptual understanding of evolution by natural selection, suggesting that more sophisticated epistemological beliefs about the structure of knowledge were correlated with high conceptual understanding scores on evolutionary theory. In particular, this finding suggests an association between an epistemological understanding of theorising knowledge as a complex system of organised theoretical principles and ideas (sophisticated simplicity epistemic beliefs) and the competence to deal effectively with complex issues like evolutionary theory (Baytelman et al, 2020a).

Our results further show that more sophisticated certainty epistemological beliefs (beliefs that knowledge is tentative and evolving) after evolution instruction were correlated with high conceptual understanding scores on evolution by natural selection. This finding is consistent with previous findings reported in the literature and highlights that students who believe that knowledge is tentative and evolving according to new evidence, new hypotheses or new interpretations of data may accept evolution by natural selection. In addition, students who believe that knowledge is tentative and evolving may perceive the existing scientific knowledge as the most valid and reliable according to the available data thus far, and may desire to continue to learn more about it, and investigate specific concepts, mechanisms and processes related to evolution, regardless of their religious beliefs or personal emotions (Harms & Reiss, 2019).

In summary, the present study extends the current literature examining relationships between epistemological beliefs and the conceptual understanding of evolution by natural selection. The findings of the present study show a statistically significant improvement in participants' epistemological beliefs (about certainty, simplicity, source, justification, and development of knowledge) after engagement in an inquiry-based intervention on evolution by natural selection over an extended period of time. Our findings also indicated a significant positive relationship between epistemological beliefs about the nature of knowledge (simplicity and certainty dimensions) before intervention and conceptual understanding of evolution by natural selection, after participants' engagement in an inquiry-based intervention on evolution.

Some limitations of this study that may give impetus to further work in this area are important to mention. The first limitation concerns the sample size. Although the issues addressed in the current study are of international applicability, we cannot generalise our results based on a relatively small sample consisting of 42 participants. The second limitation concerns the impact of the teacher on the intervention. With another teacher and the same intervention, the results may be different. The third limitation concerns the type of instrument that was used to assess epistemological beliefs. We used only a single instrument, a questionnaire, which does not probe elaborated participants' responses to items as in-depth interviews would do. Future studies could usefully take a closer look at the interplay between epistemic beliefs and argument construction using a multiplicity of methods, such as interviews and think-aloud protocols. Nevertheless, our study has important educational implications, showing improvement of participants' epistemological beliefs, after engagement in an inquiry-based intervention on evolution, over an extended period of time, as well as a significant positive relationship between epistemological beliefs of the nature of knowledge and conceptual understanding on evolution by natural selection.

In conclusion, engagement in an inquiry-based intervention on evolution by natural selection, involving collaborative work in inquiry teaching and learning activities in order to investigate specific concepts and problems related to evolution and obtain a deep conceptual understanding of the related mechanisms and processes, and facilitate discussion, interaction, and reflection upon the tasks might be a promising way for supporting both objectives, namely, acquiring content knowledge and developing more sophisticated epistemological beliefs.

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Biographical note

Andreani Baytelman, PhD, is research scientist in the field of Science Education at the Department of Education at University of Cyprus, Cyprus. Her research interests include curriculum development, instruction design, development and evaluation of biology teaching and learning material, epistemology, informal reasoning, socioscientific issues and professional development of teachers.

Theonitsa Loizou, MA, is a Biology teacher at Lykeio Paralimniou, Cyprus. Her research interests include specialized pedagogical knowledge on the fields of organization, administration, evaluation and curriculum in education, as well as in the cognitive fields of didactics of Biology and professional development of teachers.

Salomi Chatzikonstantinou, BSc, is a Biology teacher at Paralimni high school, Famagusta, Cyprus. Her reserch interests include teaching and learning biology in secondary education, as well as design, organisation and implementation of environmental and health school projects.