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The Role of Wonder in Students' Conception of and Learning About Evolution

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Learning about evolution can be challenging for students, as a full understanding may require them to see the world in new ways, to master a disciplinary language and to understand complex processes. Drawing on a long line of theoretically grounded arguments of philosophers and researchers for including wonder in science teaching, we report on the results of an empirical study with the primary aim of investigating the role of wonder in students' learning about evolution. The study was carried out through a formative intervention in which two researchers in science education collaborated with a seventh-grade teacher. Over a period of six weeks, 45 students participated in lessons and workshops aimed at eliciting a sense of wonder in relation to concepts that are known to impact the learning of evolution. We incorporated four 'triggers' to elicit students' wonder in the science class: *aesthetic experiences, defiance of expectations, agency and awareness of a mystery within the ordinary*. Logbook entries and interviews with student pairs provided empirical material for a qualitative analysis of the role of wonder in the students' meaning-making about, learning of and engagement in evolution. The results show that it is possible to design science teaching that triggers students' wonder in relation to an intended learning object. The results also reveal that the participating students described their sense of wonder in qualitatively different ways and that they still struggled to make sense of the concept of evolution after six weeks of teaching.

Keywords: evolution, formative intervention, lower secondary school, threshold concepts, wonder

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Vloga čudenja pri učencih glede pojmovanja evolucije in učenja o njej

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Učenje o evoluciji utegne učencem predstavljati izziv, saj lahko od njih terja, da morajo za popolno razumevanje uvideti svet na nove načine, da obvladajo strokovni jezik in razumejo kompleksne procese. Na podlagi dolge vrste teoretično utemeljenih argumentov filozofov in raziskovalcev za vključevanje čudenja v poučevanje naravoslovja poročamo o izsledkih empirične študije, ki je bila osredinjena na vlogo čudenja pri učenju evolucije učencev. Raziskava je bila izvedena s formativno intervencijo, v kateri sta dva raziskovalca naravoslovnega izobraževanja sodelovala z učiteljico sedmega razreda. V obdobju šestih tednov je 45 učencev sodelovalo pri pouku in na delavnicah, katerih cilj je bil vzbuditi občutek čudenja v povezavi s koncepti, za katere je znano, da vplivajo na učenje evolucije. Vključili smo štiri »sprožilce«, s čimer smo med poukom naravoslovja pri učencih izvali čudenje: estetska doživetja, kljubovanje pričakovanjem, posredništvo in zavest o skrivnosti v običajnem. Dnevniški vnosi so skupaj s tandemskimi intervjuji učencev zagotovili empirično gradivo za kvalitativno analizo vloge čudenja pri oblikovanju pomenov, ki jih imajo učenci o evoluciji, učenju in o sodelovanju pri njej. Izsledki kažejo, da je mogoče poučevanje naravoslovja zasnovati tako, da bi pri učencih sprožilo čudenje v kontekstu zamišljenega učnega cilja. Prav tako izsledki nakazujejo, da so sodelujoči učenci to opisali na kvalitativno različne načine, pri čemer so stežka osmislili koncept evolucije tudi po šestih tednih poučevanja.

Ključne besede: evolucija, formativna intervencija, nižja srednja šola, pragovni koncepti, čudenje

Introduction

The theory of evolution is one of the key explanatory models in biology. An accurate understanding of evolution is therefore essential for understanding other areas of life sciences. However, decades of research has found that both teaching and learning about evolution can be very challenging, while numerous misconceptions and alternative beliefs have been documented among students (Gregory, 2009; Groß et al., 2019; Nicholl & Davies, 2019; Pobiner et al., 2019; Sinatra et al., 2008). A number of causes have been suggested to explain students' difficulties in accurately understanding evolution, including both cognitive and emotional barriers. Cognitive barriers include conceptual difficulties, whereby evolution can be perceived as difficult because it describes complex phenomena and involves invisible and counterintuitive objects and processes (Barnes et al., 2017; Göransson, 2021). Emotional barriers, on the other hand, can arise from the human tendency to find it easier to accept things one wants to be true and more difficult to accept things one does not want to be true (Thagard & Findlay, 2010). Several studies have shown that students commonly construct teleological explanations, i.e., that changes are purpose driven, rather than using scientific explanations of evolutionary change (Gresch & Martens, 2019). In the literature, a number of sources for emotional barriers to learning about evolution have been described: students' prior beliefs that conflict with the scientific perspective of biological change, religious orientation, biological worldviews and difficulties in accepting evolutionary theory (Demastes et al., 1995; Evans, 2001). Much of the research that addresses students' difficulties in understanding evolution relies on a conceptual framework that emphasises the importance of students' meaning-making of key and threshold concepts (Meyer & Land, 2003; Tibell & Harms, 2017). Key concepts are discipline-specific theoretical descriptions that together can be used to describe scientific principles such as *origin of variation*, *differential fitness* and *inheritance*. Threshold concepts, on the other hand, describe general concepts such as *randomness*, *probability*, *spatial scales*, *adaption* and *temporal scales* (Tibell & Harms, 2017, p. 958). From an educational point of view, threshold concepts are important, as they are difficult to grasp. Once understanding is achieved, however, it represents a radical and permanent change in the way the student makes meaning about a subject (Meyer & Land, 2003). In a recent study aimed at measuring students' 'threshold crossings', Walck-Shannon et al. (2019, p. 2) describe how students »can take multiple paths oscillating in and out of a liminal state of uncertainty as they approach, learn, and master a threshold concept«.

To summarise, helping students to understand evolution is not simply a matter of supporting the cognitive aspects of learning. Teaching about evolution also needs to encompass thoughtful teaching that helps students to see the world in new and different ways. In the present study, we draw on literature that theoretically argues that wonder can make students open to this kind of transformative teaching and learning. Wonder is a so-called epistemic emotion, i.e., an affective phenomenon that is defined by a direct relation to (not) knowing and understanding (Candiotto, 2019; Valdesolo et al., 2017). Wonder is triggered by objects and events that, in a profound way, make us aware of what we do not know and cannot explain. The trigger can be various sorts of objects: the sight of a star-filled night sky, a sound, an idea or a work of art. Regardless of what triggers the sense of wonder, this emotion is defined by how it makes us aware of the fact that there is more to be learned, of the beauty or complexity of a natural phenomenon, thus forcing us to question our worldviews and stretch our minds (Candiotto, 2019; Paulson et al., 2021). In the present article, we hypothesise that making room for wonder may be one way for teachers to support students to work through the complex process of understanding evolution. We present the results from a formative classroom intervention in which a seventh-grade teacher, in collaboration with researchers in science education, developed, implemented and analysed the role of wonder as a pedagogical tool for students' engagement in meaning-making of and learning about evolution.

The aim of the study presented in this article was twofold. First, we wanted to empirically explore ways for teachers to make room for wonder in ordinary school science. Second, we wanted to investigate the ways in which such teaching might affect students' engagement in learning about evolution. The following two questions were used to guide our study:

1. In what ways can teachers make room for wonder in their science classroom?
2. In what ways, if any, does making room for wonder impact students' meaning-making, engagement in and learning about biological principles and threshold concepts that are known to be important when learning about evolution?

Wonder – A scientific emotion?

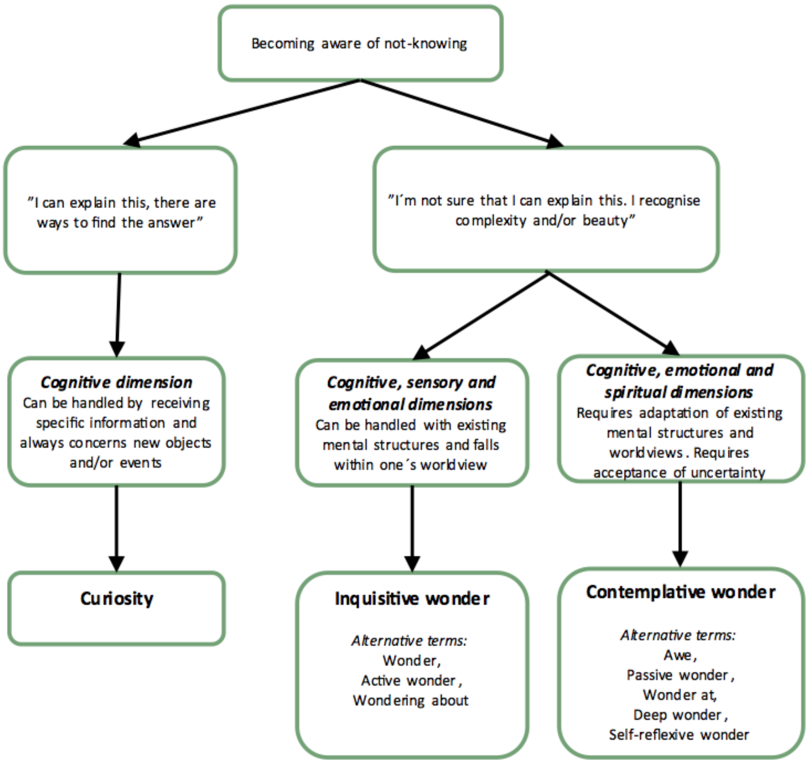
The idea of wonder being integral to learning about and understanding the world around us was suggested as early as by the ancient Greek philosophers. Plato stated that »wonder is the beginning of philosophy« and Socrates consistently urged his fellow citizens and students to consider strange new ways of looking at the world. Within the natural sciences, modern scientists such as

Richard Dawkins and Donna Strickland still highlight wonder as an indispensable dimension of the scientific endeavour (Dawkins, 2000; Strickland, 2020). In a recent study, Cuzzolino (2021) showed that epistemic emotions served as an important motivator to the »quest for understanding«, as well as a source of new perspectives on learners' work and worldview.

In general, researchers use the term wonder to address a whole range of emotions that describe not-knowing in relation to learning. For example, educational researchers refer to dichotomies such as inquisitive wonder vs. contemplative wonder, active wonder vs. passive wonder, childish wonder vs. self-reflexive wonder, and wondering about vs. wondering at (Egan et al., 2014; Hadzigeorgiou, 2011). In psychology research, where the interest in epistemic emotion has increased in the past two decades, the term *awe* is generally used (Keltner & Haidt, 2003; Valdesolo et al., 2017) to describe emotions that overlap with the term *wonder* as more commonly used in educational research. In relation to art/aesthetics, three dimensions of wonder have been described: the sensory dimension, the cognitive dimension and the spiritual dimension (Gess, 2019). Thus, in the literature referred to above, the definitions of different types of wonder sometimes overlap, but are sometimes described as distinctively different. It is beyond the scope of the present article to engage in a detailed discussion of the overlapping features and distinctions of these terms; however, to help the reader, we have summarised the main characteristics of and relationships between the common terms used to describe wonder in science education contexts (Figure 1).

Figure 1

Model of the main characteristics of and relationships between the most common terms applied to describe emotions related to not-knowing in educational research.



Note: Terms in bold are those used in the present article. Adapted from Valdesolo (2017), Wolbert and Schinkel (2021), Schinkel (2017), Egan et al. (2014) and Hadzigeorgiou (2011).

In the present article, we use the terms *curiosity*, *inquisitive wonder* and *contemplative wonder* to make distinctions between the three main types of affective response to not-knowing described in educational research. In short, curiosity covers terms that relate to a cognitive explanation-seeking response to not-knowing. The trigger for curiosity always involves a dimension of novelty, that is, it is triggered by an object or process that the person has never encountered before. Inquisitive wonder covers terms that describe experiences that are related to curiosity in that they are inquisitive, but in these cases the experience involves a cognitive as well as a sensory and emotional dimension. The trigger for inquisitive wonder may involve the dimension of novelty, but it can also involve something familiar that is seen from a new perspective (Schinkel, 2017). Contemplative wonder encompasses terms describing cognitive, emotional and spiritual experiences, i.e., when »we sense the utter mysteriousness of whatever we are contemplating« (Schinkel, 2017). The definitions of both inquisitive and contemplative wonder overlap with how the term *awe* is used within the literature. Contemplative wonder may appear to be less important for educational purposes, as it may just leave us lost for words; nevertheless, in relation to teaching and learning evolution, contemplative wonder may be of particular importance, as this type of wonder is supposed to make us stretch our minds and question our worldviews.

Wonder in school science

In line with the literature described above, arguments have been put forward to acknowledge wonder as an important dimension of school science, as well. Wonder is hypothesised to motivate students to explain and explore the physical world (Dewey, 1910; Valdesolo et al., 2017; Wolbert & Schinkel, 2021), to open an emotional relationship with nature and science content knowledge (Hadzigeorgiou & Schulz, 2014), and to predict a more accurate understanding of how science works, as well as a rejection of creationism and teleological explanations (Gottlieb et al., 2018).

Despite the fact that wonder has repeatedly been hypothesised to be beneficial to science teaching and learning, there are very few empirically based studies informing teachers how to shape their science teaching to make room for wonder. Science curricula today lack both guiding instructions and motivation for science teachers to make room for emotions (Fortus et al., 2022; Gilbert & Byers, 2017; Hadzigeorgiou, 2011; Wolbert & Schinkel, 2021). One explanation for the lack of empirical studies may be the complex and challenging demands that 'teaching for uncertainty' and making room for emotions imposes on teachers (Hadzigeorgiou, 2011; Gilbert & Byers, 2017; Wolbert & Schinkel, 2021). In making space for wonder, and therefore uncertainty, teachers need to abandon routine practices that place students' ability to articulate correct answers in the foreground. Moreover, it may be difficult to inspire teachers to make room for wonder in the classroom because they doubt the place of such emotions in science education in the first place. In a study by Stolberg (2008), pre-service teachers expressed views on wonder as something that is part of being irrational, or connected wonder to spirituality, thus positioning it as unscientific. Another reason for the lack of empirically based studies is the methodological difficulties in identifying and describing students' experiences of wonder in the ongoing reality of the science classroom.

The results of two of the few classroom-based studies of wonder are of interest for the present research. The first study, performed by Hadzigeorgiou (2011), describes a classroom intervention in which a ninth-grade physics teacher and Hadzigeorgiou together designed teaching that could foster a sense of wonder. The results showed a positive effect on students' learning of the scientific phenomena, and an increased understanding consistent with the principles of scientific methods. In the second study, Gilbert and Byers (2017) used wonder as a pedagogical tool to help primary student teachers overcome the negative associations with science that they had acquired from their own school science experiences. The results showed that the explicit use of the concept of wonder provided important insights, created a context for the students' interest in science and gave them the courage to take on science teaching. These two classroom-based studies indicate that the pedagogical potential of wonder argued for in theory may be translated into classroom practice and demonstrated how this may affect students' learning and appreciation of science. However, there is a need for more empirical studies that thoroughly study the educational potential and limitations of wonder in specific school science subjects, which is why, in our opinion, the present study is important.

Theoretical framework for wonder as a pedagogical tool in science education

In designing our strategy for the present study together with a lower secondary teacher, we were inspired by the works of Trotman (2014) and Wolbert and Shinkel (2021). Trotman (2014, pp. 36–38) draws on four biographical vignettes and some examples of educational practices to theoretically discuss the educational possibilities of and barriers to wonder in school-based education. He suggests six prerequisites for the development of wonder-full teaching: 1) an environment where exploration, chance and serendipity are valued as necessary features of education, 2) a curriculum that generates vivid imaginative and emotional connection within and across subjects, 3) empathic teaching that includes imagination, emotion and affect, 4) reception and generation of moments beyond the initial 'wow' of novelty, 5) education that is driven by neither pre-specified nor instrumental outcomes, and 6) education that includes opportunities for projects of personal interests.

The work of Wolbert and Schinkel (2021) builds on Trotman's reasoning, but is adjusted to fit the restraints of school-based teaching. Like Trotman, they recommend teaching that makes room for improvisation, imagination and the students' own interests. However, their suggestions emphasise the importance of the capacity of the teacher herself/himself to wonder, to recognise students' wonder and to see wonder in the ordinary.

The Swedish context

The education system in Sweden is based on a nine-year comprehensive school (*grundskola*), with mandatory attendance for students between seven and sixteen years of age. Secondary schooling is separated into the compulsory lower secondary (grades 7–9) and voluntary higher secondary (grades 10–12). The sample for this study comprised 45 students in one seventh-grade class (13–14 years of age).

The national curriculum that was valid when the study was carried out, Lgr 11 (National Agency for Education, 2011), regulates the aims and guidelines for all aspects of education in the comprehensive school. With regard to teaching evolution, the curriculum states: »Through teaching, pupils should get an insight into the worldview of science with the theory of evolution as a foundation, and also get perspectives on how evolution as a scientific field has developed and what cultural impact it has had« (National Agency for Education, 2011, p. 166). The core content to cover in relation to evolution is described in Table 1.

Table 1

Core content related to evolution that biology teaching should cover in grades 7–9

Section	Content to cover
Body and health	The body's cells, organs and organ systems, and their structure, function and interaction. Comparisons between man and other organisms from an evolutionary perspective. Evolutionary mechanisms and their outcomes, as well as heredity and the relationship between heredity and the environment.
Biology and worldviews	Scientific theories about the origins of life. The development of life and diversity from evolutionary theory perspectives.
Biology, its methods and ways of working	How organisms are identified, categorised and grouped, based on relationships between species and their evolution.

Note. Adapted from National Agency for Education, 2011, pp. 169–170.

Method

The study setup

The study was carried out through formative interventions. The main goal of formative interventions is to enable collaborative work between researchers and stakeholders of a specific profession in order to develop practice (Penuel, 2014). In our case, two researchers (the authors) and one teacher collaborated over a period of six weeks to design and evaluate models for introducing wonder into teaching evolution. The role of the researchers was to articulate, support and sustain the expansive transformation process within the project team (Engeström & Sannino, 2010), and to document and analyse the empirical material. The role of the teacher was to contribute professional knowledge to the planning and evaluation process and to decide on the overall setup of the six weeks of teaching so that the implementation would fit her specific class and the frame factors of the school. Prior to the intervention, the teacher and the guardians of the students received written information about the project and were informed that participation was voluntary and could be cancelled. All of the guardians were asked for written consent for their children's participation in the documented activities.

The study was preceded by a pilot study in which researchers and teachers (including the teacher in the present study) met in workshops to discuss the concept of wonder and how it might be related to teaching and learning science. During these workshops, four 'triggers' that might elicit students' wonder in the science class were jointly agreed on, drawing on theoretical frameworks suggested for teaching for wonder by Trotman (2014, pp. 37–38) and Wolbert and Schinkel (2021), as well as the participating teachers' own experiences of students' expressions of wonder in the classroom. The four triggers were: *aesthetic experiences*, *defiance of expectations, students' agency* and *awareness of a mystery within the ordinary* (Table 2).

Table 2
Descriptions of the four 'triggers' that guided the design of the workshop

Triggers	Description	Examples
Aesthetic experiences	Sensory experiences and opportunities for students to express themselves through different modes. Experiences in which mind and body are used to increase one's understanding of an object or process.	*Touch a petal to sense its softness* *Watch the glistering body of an earthworm for a long time* *Draw a detailed picture of an earthworm*
Defiance of expectations	Experiences of surprise when confronted with new aspects of something familiar, or new objects or processes in familiar settings.	*Discover that a small seed can grow into a huge sunflower* *Observing that insects have feet*
Agency	Experiences of being able to achieve something on their own or in cooperation with others.	*Design a scientific experiment on your own*
Awareness of a mystery within the ordinary	Experiencing a spiritual dimension. A feeling that 'there is more to this than what I can observe and understand'.	*Appreciate a rainbow beyond the scientific explanation of it* *A feeling of being part of something greater*

Note. Adapted from Trotman (2014, pp. 37–38), Wolbert and Schinkel (2021) and teachers' experiences of students' expressions of wonder in the classroom.

During the six-week period of the study, two lessons per week were planned covering evolution. Three of these twelve occasions were used for various workshops in which making room for wonder was explicitly planned for. In the present article, we describe the setup and results of the first workshop, which was entitled *Three Things*, and how the students responded to this intervention. The other two workshops focused on the concepts *variety, competition and natural selection* and *evolutionary time*. In the first workshop, the students were instructed to »'play' finches by using different types of 'bird beaks' (pliers) to pick food (seeds, nuts) of varying sizes and shapes«. In the next workshop, the students made a »deep time walk« along a 46 meter long string as a visual metaphor for 4.6 billion years. Key events were presented by the teacher along the way and discussed.

The design of the workshop Three Things

The workshop entitled *Three Things* was performed during a morning session when the class of 45 students were divided into three groups of 15 students who circulated between three different classrooms to enable small-group teaching in different subjects. The workshop was therefore repeated three times with three different groups, each workshop taking one hour. The workshop was introduced by the teacher, who presented three famous scientists who all had a major impact on evolutionary science: Carl von Linné (1707–1778), Mary Anning (1799–1847) and Charles Darwin (1809–1882). All three were presented in relation to their specific knowledge contribution to the field of evolution, while also highlighting how the sense of wonder was a driving force for their scientific endeavour. After this, three biological objects were presented to the students by the researchers: a tray of assorted lichens (*Cladónia spp., Cetrária islándica, Cladina spp.)*, a small trilobite fossil, and otoliths from whiting (*Merlangius merlangus)* (Figure 2). These three objects were carefully chosen for three reasons.

Figure 2

The three biological objects used in the teaching model Three Things: assorted lichens (Cladónia spp., Cetrária islándica, Cladina spp.), a trilobite, and otoliths from whiting (Merlangius merlangus)

First, these objects had been important triggers for the participating researchers' own wonder early in their careers, thus providing the students with a first-hand story of how the sense of wonder can be a driving force for scientists. Second, the objects were hypothesised to trigger the students' wonder through *aesthetic experiences*, *defiance of expectations* and *awareness of a mystery within the ordinary*. Although all of the objects were probably unfamiliar to the students, they were still expected to be perceived as ordinary (i.e., without spectacular features) at first glance. Third, all of the objects were judged to represent specific concepts that are central to learning about evolution and yet difficult to grasp: evolutionary time (the trilobite), diversity (the lichens) and organism (all three). In addition, all of the objects were reasonably accessible for a teacher and easy to handle in an ordinary classroom.

The students were divided into subgroups with five members, and each subgroup was assigned a table on which one of the objects was displayed. The students were then asked to reflect together about what they were observing when examining the object. Although the students had access to magnifying glasses during the workshop, they requested a stereo microscope, which the teacher provided for each group. After about five minutes, when the discussions seemed to be subsiding, the subgroups were asked to rotate to the next table. This procedure was repeated so that everyone had observed and examined all of the objects by the end of the workshop. The teacher and the researchers circulated among the subgroups to listen to the discussions, encourage further discussion and answer students' questions.

Students' logbook entries

In the last ten minutes of the workshop, the students were asked to reflect individually by making logbook entries on the Google Classroom learning platform. They were guided by two questions/instructions. The first instruction was: *Tell us as much as you can about what you thought about when you saw the fossil, the mushrooms/lichens, and the otoliths today*. Noteworthy here is that the teacher used the terms mushrooms and lichens interchangeably, which influenced the terms the students later used in their logbook entries. The second question was: *Do you often experience a sense of wonder? If so, what triggers this?* The students had one more opportunity to complete their reflection task. Three of the students did not attend the workshop and so only made entries corresponding to the second question.

Student interviews

At the end of the six-week period, we performed six semi-structured interviews with student pairs (Table 3). Each interview lasted about 13–16 minutes and followed an interview guide that was divided into three themes: a) the students' interpretation of the concept of wonder, b) the students' interpretation of the concept of evolution, and c) the students' experience of science teaching in general and in the three workshops of the intervention. Each interview was audio recorded and transcribed verbatim.

Analysis

Thematic content analyses were made of the logbook entries and the transcribed interviews (Table 3). Methodologically, thematic content analysis can be applied to both describing and interpreting qualitative data (Graneheim & Lundman, 2004). A central premise is that the same data material can be interpreted in several different ways. In our case, the analysis was aligned with our two research questions and made in collaboration between the authors in an iterative process for each research question, whereby we alternated between individual analyses and joint analyses of the empirical material.

Table 3
Empirical material analysed in the study

Empirical source	Description	Empirical material	Analysis
Logbook entries	Student reflections on the lesson, guided by two questions	45 digitally written individual entries	Thematic content analysis
Semi-structured and audio-recorded interviews	Student interviews in pairs, guided by thematic questions	6 audio recorded interviews with 12 students, (6 girls and 6 boys), approximately 15 minutes each	Thematic content analysis

Logbook entries

An important part of the first round of analysis was to establish how the students' expressed themselves when describing their experiences of wonder, as this would guide us in the next step, in which we wanted to analyse the students' expressions of wonder in relation to concepts connected to evolutionary processes. In order to establish how the students' expressed themselves when describing their experiences of wonder, we analysed the vocabulary they used in their entries in relation to the question: *Do you often experience a sense of wonder? If so, what triggers this?* We found a set of words that were used repeatedly by the students when they described what triggers their sense of wonder. Most commonly, the students used the words *cool* (47%) and *awesome* (36%). Other frequently used words were: *interesting*, *fascinating*, *wow!*, *weird* and '*new to me*'. For example: »*I feel a sense of wonder // when I see something that is* ***cool*** *or* ***interesting***« (Student 26).

After we had established how to guide our judgement of the students' expressions of wonder, we conducted a joint analysis of the entries that the students had made in response to the instruction: *Tell us as much as you can about what you thought about when you saw the fossil, the mushrooms/lichens, and the otoliths today*.

First, both of the researchers read all of the entries and highlighted key features of the data set in relation to research question 2. The key features were then coded individually into tentative themes. In the next step, the two sets of themes were compared and negotiated in order to consolidate them, but also to provide an opportunity for new insights into what the material could reveal in relation to the research question. This process was continued until the themes were considered stable by both researchers. Two overarching results emerged. The first comprised themes that together described *what* triggered the students' sense of wonder (Table 4), while the second set of themes described the fact that the students expressed three qualitatively different types of wonder (Table 5).

Student interviews

In order to create an overview and an overall picture of the material, the transcripts were analysed by repeated read-throughs. We then marked the sentence units, i.e., the statements in which the students' conversations were directed towards the role of wonder and learning about evolution. Other episodes were set aside. The sentence units were then analysed by condensing, coding, categorising and thematising them in the manner described above for the logbook entries (Graneheim & Lundman, 2004).

Results

Taken together, our results suggest that it is possible to design science teaching that triggers students' wonder in relation to an intended learning object. Our results also reveal that the students described their sense of wonder in qualitatively different ways, and that they still struggled to make sense of the concept of evolution after six weeks of teaching. These results are described in more detail below.

Expressing wonder associated to key and threshold concepts

Except for the three students who were absent that day, all of the students made logbook entries in which they described their experiences during the intervention. In most of the entries (25 of 42), the students' sense of wonder was triggered by one or more of the objects. On closer analysis of how the students expressed themselves, however, it was revealed that this sense of wonder could in fact be delineated into concepts that describe evolutionary or scientific processes rather than to the objects themselves.

As shown by the quotes in Table 4, the students, in their own words, associate the three objects with aspects that can be linked to evolutionary concepts such as *temporal scale, variation*, *diversity* and *interplay between organisms and habitat.*

Table 4

Students' expressions of wonder associated with evolutionary concepts

Object	Concept	Quotes	Number of entries
Lichen	Variation/ diversity	*The mushrooms were **cool** to look at with magnifying glasses; imagine how it is possible that they can look so different and still grow in the same places (log, Student 3).*	26
		The mushrooms [lichens] looked very different. Some looked very much like a mushroom and some really didn't look like a mushroom (log, Student 31).	
Trilobite	Temporal scale	*I thought the fossil [trilobite] was the **coolest** because it was about 500 million years old and yet it [the trilobite] still exists today (log, Student 15).*	25
		*It was **exciting**, it was a bit difficult to think that you can see something that existed before dinosaurs existed (log, Student 36).*	
Otolith	Variation/ diversity	*Then the one with the fish [the otolith] that you could see how long they had been alive and if they had been swimming in salt water or fresh water (log, Student 41).*	22
	The scientific process	*The otoliths were the **coolest** because there can be so much information in a tiny white blob (log, Student 34).*	
		*The otoliths were a bit **weird**, [I] didn't really know what it was used for when it was in the fish, // the fact that you can tell the age just by looking at it was really cool, but you wonder how, too (log, Student 5).*	

Note. In some cases, the student expressed wonder at more than one object. The words in bold denote the vocabulary that the students used in relation to wonder (see methods section).

The most common triggers for the students' wonder were aspects that can be related to *variation* (26 of 42 entries). As the students do not use discipline-specific language, and since their entries are rather short, it was not always possible to discern whether they were referring to variation on the individual level within one species or variation between different species. Nevertheless, the quote from Student 3 is an example of how many of the students wondered at the variation of characteristics among lichens. Student 3 remarks on the fact that the lichens looked very different even though they were all picked in the same forest. We interpret this as an emerging realisation of how variations in characteristics of an organism may, or may not, be connected to variations in the surrounding environment. Such an emerging awareness of the interplay between physical characteristics of organisms and the characteristics of the habitat in which they live is a recuring observation among the students. In several of the entries related to the otoliths, the students specifically wondered at how it was possible that the interplay between an individual and its environment could leave physical traces at a small part inside an organism.

Many of the students also wondered at the magnitude of the amount of time that has passed since the trilobites roamed the earth, and that they could nonetheless hold a specimen of this creature in their hand today. We interpret this as wonder connected to the *temporal scale* of evolutionary time, as the students explicitly describe how they find it hard to grasp the time span and fit it into their existing worldview.

Somewhat unexpectedly, our results also show that the students wonder at the scientific process itself. Student 5's comment that »*the fact that you can tell the age [of the fish] just by looking at it [the otolith] was really* ***cool****, but you wonder how, too*« was just one of several remarks that expressed wonder at how a biological object can carry information that can be interpreted and used by researchers to understand more about an individual.

Taken together, the results show that the setup of the intervention seems to have enabled most of the students to confront their own 'not-knowing' in relation to important concepts of evolutionary processes. This discovery of not-knowing was not induced by direct questions from the teacher; rather, it emerged within the students as they tried to make sense of what they were experiencing. The experience was, however, framed by an introduction that included a presentation of the concepts of both evolution and wonder. Our interpretation is that this introduction was enough to inspire most of the students to wonder about how and why the physical characteristics of species and individuals vary, as well as about the vastness of evolutionary time and the scientific process.

Three types of responses to not-knowing

When focusing our analysis on *how* the students described their experiences during the workshop, examples of the qualitatively different types of affective responses to not knowing described in Figure 1 emerged from the material (Table 5). The students described curiosity, inquisitive wonder and contemplative wonder, which we have interpreted as reflections of differences in their cognitive or/and emotional involvement.

Table 5

Types of not-knowing expressed by the students in relation to learning about evolution

	Description	Quotes	Number of entries
Curiosity	Refers to a cognitive experience. Defined by a desire to receive 'right answers'.	*There was a lot to see today, but with few answers, which was a shame (log, Student 5).* *I would really like to learn more about what we learned today (log, Student 22).* *It's like a new world that you enter and there were so many questions that came up in your head (log, Student 24).*	10
Inquisitive wonder	Refers to a cognitive, sensory and emotional experience. Defined by the student's full attention to the object of wonder and the use of both mind and body (senses) to make sense of the experience.	*When I saw the fossils it wasn't so* ***cool*** *– I've seen a lot of fossils before – but it was still nice that you could touch them, because last time I was in a place where there were fossils that you couldn't touch, but now you could (log, Student 18).* *Everything felt and smelt different. Some things had patterns on them, so it was kind of neat (log, Student 20).* *// when I looked with the magnifying glasses it looked much* ***cooler*** *and I wanted to look a lot. It was kind of a neat pattern and it was* ***cool*** *to be able to see the eyes (log, Student 23).* *The most fun was when you got to touch them [the lichens], because they didn't feel like I thought they would, far from what I thought they would feel like (log, Student 24).*	17
Contemplative wonder	Refers to a cognitive, emotional and spiritual experience. Defined by shifts in perspective (scales, complexity), and/or imagination.	*When we looked at the lichens under the magnifying glass, it was very interesting; it was like looking into another world. Everything looks so different when it's magnified (log, Student 1).* *It [the lichens] reminds me of when you were a little kid in the woods playing and seeing things like that; it was just cool and everything was* ***awesome*** *(log, Student 24).* *I thought the fossils were* ***cool****; the lichens were* ***cool*** *and looked like inspiration for children's movies with enchanted forests in them (log, Student 30).* *It was* ***exciting****; it was a little hard to think that you can see something that existed before dinosaurs existed (log, Student 36).*	17

In the first category, *curiosity*, we gathered the students' entries describing a state of not-knowing that can be resolved if, for example, someone (the teacher) gives them an answer or more information. The message conveyed by these entries corresponds in many ways with how curiosity is described in the literature. In some of the entries, we can sense frustration at the lack of information. This type of experience was the least common one.

The second category, *inquisitive wonder*, we interpret as a state of not-knowing that is simultaneously connected to cognitive, sensory and emotional qualities. The log entries reveal that the students responded to their experience of not-knowing by using both their mind and their senses to learn more. The students used sight, smell and touch to resolve their not-knowing rather than asking for information. This in turn resulted in an opportunity for sensory and emotional experiences.

The entries that were sorted into the third category, *contemplative wonder*, all reflect an emotional state in which the students let the mind wander and imagine new worlds or perspectives. Interestingly, most of these entries refer to experiences of viewing the objects through the magnifying glass or stereo microscope that the teacher provided. These devices seem to have sharpened the students' sight in a way that allowed them to enter new imaginary worlds (Students 1 and 30), but also to make way for free associations and existential thinking (Student 24).

Struggling to make sense of evolution

Learning about evolution can be challenging for students, as a full understanding may require them to see the world in a new and different way, as well as requiring a mastery of a disciplinary language and an understanding of complex processes. Accordingly, the interview transcripts revealed that, even after experiencing six weeks of teaching about evolution (encompassing approximately two lessons each week), many of the students were still struggling with how to conceptualise the main features of the evolutionary process. Our analysis of the interview transcripts reveals that the students are, as Walck-Shannon et al. (2019) put it, still in a liminal state where they are approaching and learning to master threshold concepts and a disciplinary language. When encouraged to describe what evolution is about, most of the students' descriptions were constructed by various relevant concepts, but stacked on top of each other without coherence. For example, in one of the interviews (Group 6) two students explain evolution together as follows:

Student 1: How species have changed over time to adapt more.
Student 2: Yes, adapted better. Adaptation and evolution. And species.

Even the students who specifically expressed that they perceived evolution to be logical struggled:

That like sea and land come before vertebrates in water or something like that. It's quite logical. It was quite difficult though (Group 4, Student 1)

Our interpretation of the interview data is that, at the end of the teaching period, the students had learned that there are specific concepts that should be used when describing the process of evolution. In the logbook entries made at the very beginning of the teaching period, none of the students used disciplinary concepts. Later, in the interviews, they used concepts such as *adaption*, *species* and *vertebrates*. The precision and accuracy of how to position these concepts in relation to each other and in a coherent context is, however, not yet fully developed. We suggest that this can be described as an *emerging disciplinary language*, and that the students are still struggling to master it.

In some cases (Group 5), the interview data also show, in a very explicit way, how the students were struggling with their awareness of not-knowing:

Student 1: We got to learn what came first, the atmosphere or this cell stuff and such. What else was there? We learned that humans, although we all know that from before, humans were monkeys. Or was it? Or did we bring it up? No, it wasn't that.

Student 2: No

Interviewer: Yes, what about that?

Student 2: I was told by somebody, // that you were a monkey first and then you evolved into a human being. Then more and more humans come along.

In summary, the results indicate that the full teaching period seems to have positioned the students in a liminal state where they were beginning to develop a disciplinary language but were still confused and uncertain in their understanding of evolution.

Discussion and Implications

Below we will discuss the educational implications that we identified in relation to our findings.

I. Mental guidance and providing material portals: Teachers tools for making room for wonder?

One purpose of the present study was to investigate whether it is possible to design teaching that trigger students' wonder in relation to predetermined science content. Our findings suggest that this is possible, as most of the students expressed a sense of wonder that could be connected to evolutionary concepts such as temporal scale, variation, diversity and the interplay between organisms and habitat. In previous literature, it has been suggested that the lack of empirical studies of wonder in science classrooms may be connected to the complex and challenging demands that 'teaching for uncertainty' and making room for emotions impose on teachers (Gilbert & Byers, 2017; Hadzigeorgiou, 2011; Wolbert & Schinkel, 2021). With this in mind, we were careful to plan the 'wonder workshops' based on the theoretical suggestion made by Trotman (2014) and Wolbert and Shinkel (2021) in close collaboration with the teacher who was going to perform the teaching. This teacher also had the last word on how the theoretical suggestions should be translated into teaching in her classroom. Drawing on the results of Stolberg (2008), who showed that it may be difficult to inspire teachers to make room for wonder because they doubt the place of such emotions in science education, we also placed particular emphasis on negotiating how the term wonder can be interpreted together with the teacher. This resulted in teaching in which the triggers *aesthetic experiences*, *defiance of expectations, agency* and *awareness of a mystery within the ordinary* were carefully planned for. Based on our results, we now suggest that our setup can be used by teachers as a mental tool for making room for wonder in ordinary science classrooms.

In our results, we also see examples of physical tools that directly triggered the students' sense of wonder. Since these tools seemed to instantly transfer the students to a sense of wonder, we have called them *portals*. The first portal was the carefully chosen objects (the lichens, the fossil and the otolith), which were hypothesised to trigger the students' wonder through *aesthetic experiences*, *defiance of expectations* and *awareness of a mystery within the ordinary*. In the results, there are several examples of how these objects did indeed trigger the students to express thoughts, questions and wonder. All of these objects were considered as coming from the 'real world' by the students; at the same time, the students had not experienced them in real life. It can therefore be argued that the objects made the students aware of unexpected aesthetic and mysterious qualities within something ordinary, which triggered a sense of wonder. However, our interpretation is that the pedagogical framing by the teacher was crucial for making way for their wonder. The teacher made it possible for the students to explore these objects at will, without the pressure of a predetermined learning goal. This in turn made it possible for the students to manifest *agency*, another of the theoretical prerequisites for making room for wonder. In addition, these explorations were framed by a short introduction about wonder, which may have made the students receptive to perceiving open questions and expressions of wonder as legitimate aspects of a science class. The second portal was the stereo microscope. In our empirical material, we have numerous examples of how the students were transferred to new worlds by looking through a stereo microscope and we believe that it has many functions that support this 'transfer'. First, looking through a microscope helps one to focus on an object by shielding off the classroom environment. Second, the magnification makes the details and colours of an ordinary object appear in new and unexpected ways, allowing possibilities for *aesthetic experiences*, *defiance of expectations* and *awareness of a mystery within the ordinary.* Third, the magnification provides a change in perspective related to scale, a feature previously described as an elicitor for wonder (Cuzzolino, 2021; Keltner & Haidt, 2003).

Our results exemplify how teachers can introduce objects or equipment that can function as portals for wonder in their science classroom. Most importantly, these objects and equipment do not have to be spectacular or involve advanced technology. All of the objects that were introduced in the present study are available for a teacher to bring into the classroom. Likewise, magnifying glasses and stereo microscopes can be considered to be common equipment in an ordinary classroom. This is an important result, as it exemplifies the fact that introducing wonder into the classroom can be accomplished with relatively simple means. In fact, there might be intrinsic value in choosing ordinary objects and equipment: it may serve as a strategy for ensuring that students keep their focus on the science learning object (Anderhag et al., 2016). However, using everyday equipment and ordinary objects to trigger students to wonder at our physical world requires a teacher who is able to identify the wonder within the ordinary (Wolbert & Schinkel, 2021) and who feels comfortable with introducing the concept of wonder into the science classroom (Stolberg, 2008). It is therefore important to bear in mind that the role of the teacher is crucial. In our example, the teacher not only provided 'portals', but did so in combination with explicit guidance that introduced the concept of wonder and demonstrated how this emotion is valid in science. The results can thus be related to the conclusions of a study by Gilbert and Byers (2017) in which the explicit use of the term wonder in connection with science teaching was described as working as a catalyst for early childhood student teachers' interest in and understanding of the scientific endeavour.

II. Students respond in different ways to teaching for wonder

Our results show that 'wonder-infused' teaching evoked students' *curiosity*, *inquisitive wonder* and *contemplative wonder* (Table 5). Based on the results, we suggest that teachers need to be sensitive towards the different ways in which students respond to teaching that makes room for wonder. Some students responded with *curiosity*, which contrasts with inquisitive and contemplative wonder in that it is primarily focused on a cognitive striving for answers. This response therefore lacks the sensory, emotional and spiritual dimensions that wonder encompasses. Curiosity is nevertheless an expected response to teaching that makes room for students' own explorations and open questions. According to Lindholm (2018), inquisitiveness for facts and classical knowledge is especially predominant in prepuberty, which is a phase that the students of the present study were just leaving. Teachers trying to elicit wonder in their lower secondary science classes should therefore also be prepared to support students who ask for more information. In the case of learning about evolution, facts and examples of diversity among species and animal anatomy, which the teacher is able to provide, can in the long run be sources of wonder.

In our material, the students predominantly expressed *inquisitive wonder*. Based on how the students expressed themselves, we conclude that their inquisitive wonder was mainly triggered because they were able to engage with the objects without a predetermined protocol. As discussed in the previous section, the students were empowered to pursue explorations of their own design. This resulted in physical explorations in which they used several of their senses. A number of the students noted in their logbooks that it was unusual to actually be able to touch and smell the objects that they encountered in science education. The sensory experiences seem to have opened the possibility of emotional responses towards the object in a way that a picture in a book or displayed in a PowerPoint presentation cannot accomplish. However, the students were also given an opportunity to experience authentic moments of discovery, which are common triggers for wonder (awe) for professional scientists (Cuzzolino, 2021).

A few of the students in our study also expressed *contemplative wonder* in their logbook entries. At first sight, this type of wonder might appear to be anti-educational, because, as Schinkel (2017, p. 538) remarks, »it is not inherently inquisitive like active [inquisitive] wonder and, as a response to mystery, may leave us lost for words«. However, we agree with Schinkel's conclusions that contemplative wonder may still have an important function in science teaching, as this emotion can make students receptive to discussions about different perspectives and the limits of our understanding. In relation to teaching and learning about evolution, such discussions can make way for the transformative experience that is necessary in order to fully understand evolutionary processes. We therefore propose that this type of wonder might be a specifically helpful tool for teachers to support students to accomplish the threshold crossing described by Walck-Shannon et al. (2019).

III. Crossing a threshold of learning requires support for disciplinary language acquisition

As previously described in the literature, threshold concepts are fundamental concepts that, once understood, transform a student's perception of an entire subject and enable access to a previously inaccessible way of thinking, understanding or interpreting something (Meyer & Land, 2003; Walck-Shannon et al., 2019). It is therefore interesting to note that the students involved in the present study *independently* wondered at concepts that are considered as key or threshold concepts for thinking about and understanding evolution. When doing so, the students did not use the specific concepts of evolution, but rather described the phenomena in their own words. This is not surprising, as the written reflections were made at a time when the students had not yet learned any of the relevant concepts. At the end of the teaching period, they nevertheless tried to use the concepts, but were still unsure of how to do so correctly. According to Walck-Shannon et al. (2019, p. 2), »the process of crossing a threshold of learning is accompanied with disciplinary language acquisition that is bounded and specific to the threshold concept«. We therefore suggest that making room for wonder when teaching evolution be combined with support for the student's development of a disciplinary language.

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References

Barnes, M. E., Evans, E. M., Hazel, A., Brownell, S. E., & Nesse, R. M. (2017). Teleological reasoning, not acceptance of evolution, impacts students' ability to learn natural selection. *Evolution: Education and Outreach*, *10*(1). https://doi.org/10.1186/s12052-017-0070-6

Candiotto, L. (2019). Epistemic emotions: The case of wonder. *Revista de Filosofia Aurora*, *31*(54). https://doi.org/10.7213/1980-5934.31.054.DS11

Cuzzolino, M. P. (2021). »The awe is in the process«: The nature and impact of professional scientists' experiences of awe. *Science Education*, *105*(4), 681–706. https://doi.org/10.1002/sce.21625

Dawkins, R. (2000). *Unweaving the rainbow: Science, delusion and the appetite for wonder*. HMH.

Demastes, S. S., Settlage Jr., J., & Good, R. (1995). Students' conceptions of natural selection and its role in evolution: Cases of replication and comparison. *Journal of Research in Science Teaching*, *32*(5), 535–550. https://doi.org/10.1002/tea.3660320509

Dewey, J. (1910). Science as subject-matter and as method. *Science*, *31*(787), 121–127.

Egan, K., Cant, A. I., & Judson, G. (2014). *Wonder-full education: The centrality of wonder in teaching and learning across the curriculum*. Routledge.

Engeström, Y., & Sannino, A. (2010). Studies of expansive learning: Foundations, findings and future challenges. *Educational Research Review*, *5*(1), 1–24. https://doi.org/10.1016/j.edurev.2009.12.002

Evans, E. M. (2001). Cognitive and contextual factors in the emergence of diverse belief systems: Creation versus evolution. *Cognitive Psychology*, *42*(3), 217–266. https://doi.org/10.1006/cogp.2001.0749

Fortus, D., Lin, J., Neumann, K., & Sadler, T. D. (2022). The role of affect in science literacy for all. *International Journal of Science Education*, *44*(4), 535–555. https://doi.org/10.1080/09500693.2022.2036384

Gilbert, A., & Byers, C. C. (2017). Wonder as a tool to engage preservice elementary teachers in science learning and teaching. *Science Education*, *101*(6), 907–928. https://doi.org/10.1002/sce.21300

Göransson, A. C. (2021). *Crossing the threshold: Visualization design and conceptual understanding of evolution*. http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-173337

Gottlieb, S., Keltner, D., & Lombrozo, T. (2018). Awe as a scientific emotion. *Cognitive Science*, *42*(6), 2081–2094. https://doi.org/10.1111/cogs.12648

Graneheim, U. H., & Lundman, B. (2004). Qualitative content analysis in nursing research: Concepts, procedures and measures to achieve trustworthiness. *Nurse Education Today*, *24*(2), 105–112. https://doi.org/10.1016/j.nedt.2003.10.001

Gregory, T. R. (2009). Understanding natural selection: Essential concepts and common misconceptions. *Evolution: Education and Outreach*, *2*(2), 156–175. https://doi.org/10.1007/s12052-009-0128-1

Gresch, H., & Martens, M. (2019). Teleology as a tacit dimension of teaching and learning evolution: A sociological approach to classroom interaction in science education. *Journal of Research in Science Teaching*, *56*(3), 243–269. https://doi.org/10.1002/tea.21518

Groß, J., Kremer, K., & Arnold, J. (2019). Evolution learning and creationism: Thinking in informal learning environments. In U. Harms & M. J. Reiss (Eds.), *Evolution education re-considered: Understanding what works* (pp. 285–305). Springer International Publishing. https://doi.org/10.1007/978-3-030-14698-6_16

Hadzigeorgiou. (2011). Fostering a sense of wonder in the science classroom. *Research in Science Education*, *42*(5), 985–1005. https://doi.org/10.1007/s11165-011-9225-6

Hadzigeorgiou, & Schulz, R. (2014). Romanticism and romantic science: Their contribution to science education. *Science & Education*, *23*(10), 1963–2006. https://doi.org/10.1007/s11191-014-9711-0

Keltner, D., & Haidt, J. (2003). Approaching awe, a moral, spiritual, and aesthetic emotion. *Cognition and Emotion*, *17*(2), 297–314. https://doi.org/10.1080/02699930302297

Lindholm, M. (2018). Promoting curiosity?: Possibilities and pitfalls in science education. *Science & Education*, *27*(9–10), 987–1002. https://doi.org/10.1007/s11191-018-0015-7

Meyer, J. H. F., & Land, R. (2003). Threshold concepts and troublesome knowledge: Linkages to ways of thinking and practising within the disciplines. *ISL10 Improving student learning: Theory and* *practice ten years on*, 412–424.

National Agency for Education. (2011). *Läroplan för grundskolan, förskoleklassen och fritidshemmet 2011*. Fritze distributör. http://www.skolverket.se/publikationer?id=2575

Nicholl, J., & Davies, P. (2019). Participating in an object-based learning project to support the teaching and learning of biological evolution: A case study at the grant museum of zoology. In U. Harms & M. J. Reiss (Eds.), *Evolution education re-considered: Understanding what works* (pp. 307–330). Springer International Publishing. https://doi.org/10.1007/978-3-030-14698-6_17

Paulson, S., Shiota, M. »Lani«, Henderson, C., & Filippenko, A. V. (2021). Unpacking wonder: From curiosity to comprehension. *Annals of the New York Academy of Sciences*, *1501*(1), 10–29. https://doi.org/10.1111/nyas.14317

Penuel, W. R. (2014). Emerging forms of formative intervention research in education. *Mind, Culture, and Activity*, *21*(2), 97–117. https://doi.org/10.1080/10749039.2014.884137

Pobiner, B., Watson, W. A., Beardsley, P. M., & Bertka, C. M. (2019). Using human examples to teach evolution to high school students: Increasing understanding and decreasing cognitive biases and misconceptions. In U. Harms & M. J. Reiss (Eds.), *Evolution education re-considered: Understanding what works* (pp. 185–205). Springer International Publishing. https://doi.org/10.1007/978-3-030-14698-6_11

Schinkel, A. (2017). The educational importance of deep wonder. *Journal of Philosophy of Education*, *51*(2), 538–553. https://doi.org/10.1111/1467-9752.12233

Sinatra, G. M., Brem, S. K., & Evans, E. M. (2008). Changing minds? Implications of conceptual change for teaching and learning about biological evolution. *Evolution: Education and Outreach*, *1*(2), 189–195. https://doi.org/10.1007/s12052-008-0037-8

Stolberg, T. L. (2008). Wither the sense of wonder of pre-service primary teachers' when teaching science?: A preliminary study of their personal experiences. *Teaching and Teacher Education*, *24*(8), 1958. https://doi.org/10.1016/j.tate.2008.05.005

Strickland, D. (2020). »Science is about wondering why.« *Nobel Media AB*. https://www.nobelprize.org/donna-strickland-science-is-about-wondering-why/

Thagard, P., & Findlay, S. (2010). Getting to Darwin: Obstacles to accepting evolution by natural selection. *Science & Education*, *19*(6–8), 625–636. https://doi.org/10.1007/s11191-009-9204-8

Tibell, L. A. E., & Harms, U. (2017). Biological principles and threshold concepts for understanding natural selection. *Science & Education*, *26*(7), 953–973. https://doi.org/10.1007/s11191-017-9935-x

Trotman, D. (2014). Wow! What if ? So what?: Education and the imagination of wonder: Fascination, possibilities and opportunities missed. In *Wonder-Full Education*. Routledge.

Valdesolo, P., Shtulman, A., & Baron, A. S. (2017). Science is awe-some: The emotional antecedents of science learning. *Emotion Review*, *9*(3), 215–221. https://doi.org/10.1177/1754073916673212

Walck-Shannon, E., Batzli, J., Pultorak, J., & Boehmer, H. (2019). Biological variation as a threshold concept: Can we measure threshold crossing? *CBE—Life Sciences Education*, *18*(3), ar36. https://doi.org/10.1187/cbe.18-12-0241

Wolbert, L., & Schinkel, A. (2021). What should schools do to promote wonder? *Oxford Review of Education*, *47*(4), 439–454. https://doi.org/10.1080/03054985.2020.1856648

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