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Developing Teacher Competencies for Teaching Evolution across the Primary School Curriculum: A Design Study of a Pre-Service Teacher Education Module

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Abstract: Numerous studies indicate that evolutionary concepts can and should be taught at the primary school level. However, teaching evolution in primary school is presumably not yet the norm globally. At the same time, the educational potential of evolutionary concepts lies in their applicability to many curriculum topics in the natural and social sciences. Capitalizing on this potential requires broad teacher content knowledge (CK) and pedagogical content knowledge (PCK) about the teaching of evolutionary concepts. However, not much is known regarding ways to develop primary teacher CK and PCK during pre-service training. In this article, we present the iterative design, implementation, and mixed methods formative evaluation (based on a design-based research framework) of a pre-service teacher education module. Its aim was to promote the development of pre-service primary school teacher CK, PCK, as well as motivation and confidence for teaching evolution across the primary school curriculum. Results indicate that pre-service teachers can be supported and motivated to teach evolutionary concepts across various themes in the primary school curriculum through a semester long course. Participants were able to develop core aspects of CK and PCK regarding the teaching of evolutionary concepts in primary school. The resulting module design integrates existing collective PCK on teaching evolution at the primary level as well as novel design considerations and teaching approaches that can be integrated into pre-service teacher education programs. However, challenges remain, particularly regarding the integration of evolutionary concepts in mandated curriculum standards such that the educational potential of evolution can be fully capitalized on by teachers.

Keywords: evolution; human evolution; social–emotional learning; teacher education; primary school; pedagogical content knowledge

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1. Introduction

Most people familiar with evolutionary theory will also be familiar with the mantra that "Nothing in biology makes sense except in the light of evolution" [1]. At the same time, it continues to be a challenge to situate evolutionary theory in the curriculum in such a way that it can actually deliver on this mantra. Evolution is usually still treated as a topic, covered as such in textbooks [2]. It has also been argued that a narrow framing of evolutionary themes and concepts might be partly responsible for the difficulty of establishing the centrality of evolution across the curriculum.

Many educators and education researchers have also recognized the role of early evolution education in shaping students' conceptual understanding of evolutionary concepts and principles (e.g., [3,4]). A range of approaches have been developed in recent years that indicate that, despite the potential for a diversity of initial misconceptions and biases,

young students can learn and understand concepts and processes like variation, inheritance, natural selection, drift, and phylogenetic trees (e.g., [5,6]; see also Section 2.3). However, studies also show that students' understanding of natural selection tends to fade and revert back to previous intuitive conceptions after a few months (e.g., [7]). Overall, from the perspective of conceptual change literature, modifying intuitive preconceptions is often a gradual and long-term process requiring multiple, regular exposure to and construction of alternative conceptions [8]. Similarly, from the perspective of the transfer of the learning literature, students' ability to transfer their understandings of concepts and principles to new contexts is enhanced when students have the opportunity to investigate these concepts across a range of example phenomena and through a range of representations [9–11].

This indicates that also in primary school, evolution should be taught not so much as a separate topic to be covered once and checked off as completed, but rather as a conceptual lens that can help make sense of many phenomena across grades. This in turn requires teachers' knowledge and competency to see how evolutionary concepts apply across a range of phenomena and to orient instructional methods in order to help students develop deeper conceptual understandings.

Not much is known about how teacher education and professional development programs or educational materials can prepare (primary school) teachers to develop this kind of interdisciplinary pedagogical content knowledge.

This study aimed to explore whether a pre-service teacher education module can be designed that supports the development of participants' (throughout the manuscript, we use the term "participant" for pre-service teacher students participating in the studies, and the term "student" for primary, secondary or undergraduate students in general.) content knowledge, pedagogical content knowledge as well as attitudes, motivation, interest, and confidence for teaching evolutionary concepts across the curriculum. The study is embedded in a larger design-based research project by the authors [12] he aim of the project is to integrate behavioral and evolutionary science into curricula and teaching practice across grades and subjects towards the development of conceptual understandings of human behavior and social–emotional competencies among students and teachers.

Using the design-based research approach [13–15], the study reported here can be situated in the stages of preliminary research and analysis, intervention design as well as formative evaluation of design.

Related to these phases, and following recommendations by [13], the main and sub-research questions of the study are: How can a semester-long module support pre-service teachers to develop content knowledge, pedagogical content knowledge as well as attitudes, motivation, interest, and confidence for teaching evolutionary concepts across the primary school curriculum?

(a) What needs, opportunities, and initial module design conjectures can be identified from the existing literature and curriculum contexts? [preliminary research, analysis phase]
(b) What constitutes a pre-service primary teacher education module that has the potential to develop participant content knowledge, pedagogical content knowledge, as well as attitudes, motivation, interest, and confidence to teach evolutionary concepts across various curricular themes and subjects? [design phase]
(c) What challenges and opportunities emerge across two cycles of design implementation and adaptation at a German university? [formative evaluation]
(d) What participant content knowledge, pedagogical content knowledge, as well as attitudes, motivation, interest, and confidence for teaching evolution in primary school can be observed during and after module implementations? [formative evaluation]

Addressing research subquestion a, the following Section 2 summarizes the synthesis of curriculum context and the literature regarding the teaching of evolution in primary school for the identification of needs, opportunities, and knowledge gaps that informed the module design. In Section 3, we address research subquestion b and describe the process of iterative module design, including the context of module implementation which

added further needs and opportunities. We also describe here methods of data collection (many of which are themselves elements of the module design in the form of formative and summative assessment methods) during module implementations and evaluations. Section 4 presents a selection of results to address research subquestions c and d regarding the formative evaluation of module implementation.

2. Background: Synthesis of Context and Literature

2.1. Evolutionary Concepts in Primary School Curriculum Standards

No comprehensive review or comparison of international primary school curriculum standards regarding their integration of evolutionary concepts appears to exist (one attempt is, e.g., [16], Additional File S1, who mapped the content of their proposed activities to primary school curricula in Brazil, Canada, France, Portugal, the UK, and the US). Nonetheless, there are indications that there is a high degree of variation across countries. For example, in the US the Next Generation Science Standards include evolutionary concepts across grades 1–4 [17]. Grade 1 includes the core ideas of "Inheritance of Traits" and "Variation of Traits"; grade 3, the core ideas of "Evidence of Common Ancestry and Diversity", "Adaptation", "Inheritance of Traits", "Variations of Traits", and "Natural Selection"; and grade 4, the core idea of "History of Planet Earth." In Germany, however, evolutionary concepts are hardly included in current primary school (grades 1–4) curriculum standards. The German primary school subject of *Sachunterricht* is a multidisciplinary subject integrating natural science, social science, geography, history, cultural, and technical perspectives [18]. In the national framework for the German *Sachunterricht* [18] as well as across *Sachunterricht* curricula of 16 German states, the terms evolution, inheritance, selection, do not appear at all. However, a few evolutionary concepts appear implicitly or explicitly in standards and teaching materials. Most but not all curriculum standards make reference to "adaptation" or "adaptedness." However, the term adaptation is often used in at least two ways: in the evolutionary sense, as well as in the sense of adapting one's behavior to certain circumstances [19]. It is not made clear how exactly students might attain or relate to these diverse uses of adaptation as a concept within biology and other disciplines. Four state curricula make reference to the "stone age", one curriculum makes reference to fossils and one makes reference to family trees.

2.2. The Need to Teach Evolutionary Concepts in Primary School

Given the sporadic to non-existent explicit treatment of evolution in current German primary school curricula, one might assume that primary school teachers do not need to be equipped with any knowledge and competencies regarding the teaching of evolution. Here we argue that this stance is misguided for several reasons.

One reason evolution should be taught in primary school is the potential of addressing misconceptions and building a solid foundation of scientifically accurate conceptual understandings. As has been noted by others [4,16], treating the concept of adaptation or adaptedness of traits without also exploring the (evolutionary) causes for this adaptedness runs the danger of leaving misconceptions unchallenged or even reinforcing them, such as inadequate teleological or creationist beliefs. It also hinders students in understanding and evaluating the possible impacts of human action on the environment and on species.

For example, in the German national framework for *Sachunterricht* [18], we find an example lesson on the shapes of seeds. The text states "Questions emerge regarding the *causes* or *purpose* that these different shapes of seed wings have. Why do some seeds have wings, others not? Why do some seeds have big wings, others small wings?" ([18]; p. 97, own translation from German, emphasis added). However, while asking for "causes", the text does not include the treatment of evolutionary causes, particularly random variation and natural selection, to help students understand the mechanism that led to these currently observable functional traits. We observe in the framing a muddling of cause and function/purpose that, within the evolution education literature, is often regarded as highly problematic as it reinforces problematic forms of teleological thinking (e.g., [20]).

At the same time the lesson in fact offers bits of text and explanations that go a long way towards providing answers to the question of evolutionary cause, yet the evolutionary logic of these pieces of information is not made explicit to teachers nor students.

Another reason to integrate evolution education in primary grades is the aforementioned role of evolutionary concepts in understanding the natural world—they are lenses that help to understand and relate a variety of phenomena. Evolutionary concepts should thus be woven in and addressed across themes in instruction. As others have similarly highlighted (e.g., [16,21]), many concepts and learning goals in primary school curricula can in fact be connected into the goals of evolution education (i.e., developing conceptual understanding of evolutionary concepts), but this may require a more explicit evolutionary framework such that teachers and students can come to understand the evolutionary logic of the phenomena they are exploring.

Similarly, an increasing diversity of resources exists that are exposing younger children to evolutionary ideas. For example, we have collected a database of more than 80 children's books across several languages that cover various evolutionary themes (see Supplementary Materials, Additional File S1). However, these books may not necessarily present information in a way that is congruent with current best practice in evolution education and may in fact rather reinforce various misconceptions [19].

Thus, teachers need to be supported to critically assess the usefulness of materials available to them in their context regarding the development of scientific understandings. At the same time, teachers need to be enabled to make use of local opportunities such as student interests and questions, curriculum themes and learning goals, current events and media, informal learning places like zoos and museums, and other locally available materials that provide (possibly implicit) opportunities for teaching evolutionary concepts.

For these reasons, we argue that primary school teachers need to be supported to develop pedagogical content knowledge to teach evolutionary concepts, not just in a separate unit about evolution and with a concrete and prescribed set of topics and instructional methods (as, e.g., indicated by [22]), but across a range of phenomena and using a diversity of methods, flexibly adapted to their context. This also includes developing teachers' ability to "see" evolutionary concepts in the curriculum and in teaching materials, even if they are not explicitly stated in wording, and to derive "teachable moments" towards a conceptual understanding of evolutionary concepts and for addressing possible misconceptions. This identified need represents one of the main rationales for this study.

2.3. Content Knowledge and Pedagogical Content Knowledge for Teaching Evolution in Primary School

Teacher professional knowledge is usually conceptualized as consisting of several domains, including content knowledge (CT; of a subject, topic or concept), pedagogical knowledge (knowledge regarding the nature of teaching and learning), and pedagogical content knowledge (PCK; knowledge about curriculum goals, student understandings and learning difficulties, instructional strategies, and assessment related to a subject, topic, or concept; [23]). PCK has also been further differentiated into collective, personal, and enacted PCK [24].

Various assessment tools have been developed and used to assess evolution understanding of high school and undergraduate students as well as evolution CK of pre-service and in-service teachers (see [25,26] for reviews). A recent and comprehensive assessment instrument is the Knowledge About Evolution 2.0 instrument (KAEVO 2.0) which integrates components of previous questionnaires and thus aims to cover a diversity of evolutionary themes and concepts [27]. Kuschmierz et al. [28] report on a study using the instrument across 26 European countries with first-year university students enrolled in biology-related as well as non-biology related programs. Authors found that students across countries had a rather low knowledge of evolution, with 47% of students in biology-related programs and 76% of students in non-biology-related programs categorized as "Very low knowledge". Torkar and Sorgo [29] used part of the KAEVO 2.0 to assess Slovenian pre-service primary

school teachers' CK and also found very low levels of knowledge. In the current study, select questionnaire items of the KAEVO 2.0 were included in the (second) module design as formative assessment and discussion tools.

Various studies also clarified or assessed PCK around teaching evolution. Ziadie and Andrews [30] reviewed the extent of *collective* PCK (sensu [24]) resulting from peer-reviewed literature on the teaching of evolution in high school and undergraduate level, highlighting certain knowledge gaps. While no such review appears to exist regarding collective PCK on the teaching of evolution at the primary school level, aspects of PCK have been explored or reviewed in a number of studies. For example, Bruckermann et al. [5] reviewed young children's (up to 7 years) pre-conceptions and potential learning difficulties about evolutionary concepts of variation, inheritance, and natural selection. Many studies have contributed instructional strategies for the teaching of evolutionary concepts in primary school, summarized in Table 1. Several learning progressions have also been proposed on teaching evolutionary concepts in primary school [31–33], together with proposed instructional strategies.

Thus, it can be said that the evolution education literature is making progress in establishing elements of collective PCK regarding the teaching of evolution in primary school. This literature can increasingly inform primary science teacher educational programming towards the development of teacher personal PCK. The literature reviewed here, as well as further English- and German-language publications and materials around teaching evolutionary concepts in primary school, were thus used to inform the module design and/or included as content and materials (see Supplementary Materials, Additional File S1).

Despite these advances in collective PCK, not many studies exist around developing and evaluating primary school teachers' *personal* and *enacted* PCK (sensu [24]) on teaching evolution. Asghar et al. [34] explored the attitudes and knowledge of pre-service primary school teachers in Canada around teaching evolution through surveys and interviews, and concluded that study participants lacked sufficient CK and PCK about evolution despite evolution being integrated in the curriculum. Similarly, Billingsley et al. [35] explored the attitudes of pre-service primary school teachers in the UK through a survey and found that the majority of participants had a positive attitude about the importance of teaching evolution in primary school and the recent inclusion of the topic in the English 6th grade curriculum, but only a quarter agreed that they had an adequate understanding of evolution to teach it.

Table 1. Overview of methods to teach core evolutionary concepts in primary school synthesized from the existing literature.

Themes, Concepts	Instructional Materials and Methods	Subject Connections	References
Within-species variation in traits, addressing essentialism	documenting variation of select traits in the class as well as among other species (animals and plants)	Science, math	[16,21,22,32,33,36–39]
History of life, deep time thinking	creation of timelines of various scales	Math	[22,33,40] *
	dioramas of epochs of earth history	Art	[40] *
	handling of fossils and modeling the process of their creation	Earth science/geography, history (historic sources), art	[33], [40] *, [41]
	Dinosaurs	Science, history, art	[41]

Table 1. *Cont.*

Themes, Concepts	Instructional Materials and Methods	Subject Connections	References
Common ancestry, family relationships, phylogenetic trees, and tree thinking	creation of students' family trees of relatives	History, social studies	[16]
	modeling of evolutionary trees using a variety of materials (tree branches, mobiles)	History, art	[33]
	grouping and sorting activities to approach systematics and the conversion into a phylogenetic tree	science	[16,42]
	Identifying and modeling homologies	science	[22]
Functions of traits, adaptation	Explore a variety of organisms in their environments and how their traits function to fulfill a variety of needs (using students' intuitive abilities to see function and need as stepping stones)	Science	[16], [40] *, [43], [44] *; but see [45]
Inheritance of traits	Observing likeness between parents, offspring, siblings	Science	[16]
	Seed saving/breeding of plant varieties	Science, school gardens	[36]
	Differentiating between genetically (biologically) inherited traits and culturally inherited (socially learned) traits by use of adoption and migration vignettes	Social studies	[46]
Natural selection (addressing teleological thinking)	Differentiate the question why a (adaptive) trait exists into the question "What is the trait for" [function] and "How did the trait come about" [past processes of natural selection]	Science, language	based on [47]
	Pictures and story books with guided discussions	Science, language, art	[7,48–52]
	Simulation games and other role-playing activities	Science	[16], [40] *, [44,48]
	Domesticated animals and artificial selection of domesticated plants	Science, school garden	[36]
	Computer models	Science	[53,54]
Drift, founder effect	Simulation games	Science	[16]
Isolation	Stories and discussions of a species separated into different islands	Science, geography	[40] *
Sexual selection	Materials on the peacock	Science, art	[40] *

* No empirical evidence was available regarding the effectiveness of these materials in classrooms.

Overall, PCK on evolution of mostly secondary in-service and pre-service teachers has been assessed using survey instruments (e.g., [55–57]), simulated classroom environments [58], as well as interviews, observations, and analysis of artifacts (e.g., [59–61]). In this study, qualitative and quantitative methods were used to assess participant CK and PCK, including through the analysis of PCK elements in participant artifacts and questionnaire responses (see Section 3.3).

2.4. Opportunities for Teaching Evolution across the Primary School Curriculum

Within the larger design-based research project that this study is part of [12] authors, 2020), the rationale for teaching evolutionary concepts extends to the development of social–emotional competencies and transferable understandings of human behavior and culture. Thus, a further aim of this review of the literature was to identify opportunities to expand the teaching of evolutionary concepts in primary school beyond the natural domain and to connect to curriculum goals and instructional methods in the social, cultural, and technical domains as well as in the domain of social–emotional learning.

2.4.1. Connections to Curriculum Goals in Social–Cultural and Technical Education

Evolutionary concepts have increasingly informed and shaped fields beyond biology, particularly with the emergence of the field of cultural evolution [62]. Overall, the theme of cultural evolution does not yet seem to be widely integrated in evolution education standards and practice and its potential remains relatively unexplored in evolution education [63]. One might also think that cultural evolution is too advanced a theme for primary school. However, the literature review revealed that a variety of approaches and materials exist that indicate that even primary school aged children are already exposed to such ideas, and that they may hold significant learning potential. Thus, cultural evolutionary concepts may productively connect to curricular themes related to technology and culture (which are also included in the German *Sachunterricht*).

One primary school evolution education material that includes cultural evolution is the EvoKids textbook by [40]. In fact, the book includes a lesson plan for "Evolution of a paper plane" (p. 73 ff.) within the section of mechanisms of evolution, meant to help students understand the process of adaptation by natural selection through the analogy with successive improvements and selection of paper plane designs by trial-and-error. Interestingly, the "Evolution of a paper plane" lesson plan is not included within the book's section on cultural evolution and no reference is made to the cultural evolutionary dynamics of the activity. At the same time, this activity is in fact equivalent to the paradigm of transmission chain experiments in cultural evolution [64]. For example, ref. [65] used this paradigm and developed experiments around the successive improvement of paper planes and "spaghetti towers" with participants aged 11 years and above to study cultural evolutionary processes. Similarly, ref. [66] studied the role of teaching and language in the transmission of stone tool making. Their experimental setup in part resembles the games of Chinese whispers or Charades, which equally highlight the function of human language for the transmission of cultural information.

Furthermore, themes and instructional methods in evolution education usually focus on genetically inherited biological traits and may even discourage the discussion of other traits and mechanisms of their transmission (e.g., [16]). In this regard, framings can sometimes be problematic in terms of reinforcing genetic determinism (and with possible implications for social–emotional development). For example, in [40], when introducing the concepts of variation and inheritance, the text reads "What would it be like if we all looked exactly the same, and had the same hobbies and skills? (. . .) The fact that each one of you has different features is to do with your body's cells storing different hereditary information. Half of this comes from your mother and half from your father". It seems problematic to frame complex traits like hobbies and skills as being caused exclusively by genes (and hence, more or less predetermined or difficult to change).

At the same time, there are indications that primary school aged children can be supported in distinguishing between different kinds of traits and their biological and cultural forms of transmission. Moya et al. [46] showed that 4–10 year old children across cultures (Peru, Fiji, USA) think most traits are biologically transmitted from parents, but by middle childhood (9 years and above), children increasingly differentiate between traits that are biologically inherited (such as morphological traits) and traits that are culturally inherited from parents or the social environment (such as knowledge and beliefs). It is an open question how such insights and methods might inform instructional strategies towards an understanding of biological and cultural inheritance in evolution education.

2.4.2. Connections to Social–Emotional Learning Goals

Another relatively unexplored dimension of teaching evolution, in primary as well as secondary school, is its relation to social–emotional learning and development of competencies such as growth mindset, self-regulation, perspective-taking, and cooperation.

The literature review suggests that, often, examples of themes and instructional methods in primary evolution education (as well as in secondary education) focus on the role of competition, predator–prey dynamics, and individual-level natural selection (e.g., most of the literature in Table 1). Conversely, the evolution of cooperation is much less of a focus and may be perceived as a topic for advanced evolution education (see also [30,67]). However, cooperation is an important factor in the evolution of many species including humans. We argue that understanding the role of cooperation in our species can be a core component of developing cooperation competencies (see also [67,68]). In the course of module development, we found that simulation games to teach the logic of natural selection can be modified to teach the evolution of cooperation, and they thus resemble cooperation games that are used in behavioral experiments to study human social behavior (e.g., [69]). Various cooperation games are often already used in primary and secondary education to develop cooperation competency and an understanding of the need for cooperation in society (e.g., [70]), and these can be extended to explore the functions of various human behaviors (e.g., communication, sense of fairness, empathy) as well as the evolutionary origins of these traits. Thus, an instructional material that emerged during module design was a cooperation game that simulated a stone age collective hunt and the challenges of cooperation and collective action inherent in this situation, based on the game theoretic models of the "stag hunt" and the "public goods game" as collective action problems [71,72], and highlighting how cooperative abilities are advantageous in such situations.

Implications for social–emotional learning also present themselves when teaching foundational evolutionary concepts like variation and natural selection. For example, an approach to help students see within-species variation is to explore variation among students in the class (e.g., [16,22], see Table 1). An issue that has apparently not been addressed so far is the ethical and social–emotional implications of doing this. After all, it can be problematic to highlight variations in traits like weight or skin color. Additionally, it is scientifically incorrect and pedagogically problematic to connect trait variation among students to the idea of "adaptation" and "natural selection", with potentially harmful implications that some students in class are "better adapted" than others. This issue was explicitly addressed in the module in the form of a structured group discussion asking—why might it be problematic pedagogically to highlight variations among students in class, and how might one deal with this in the classroom. Overall, when exploring trait variation in the classroom it might be important to also point out the fact that not all traits have functions that are relevant for survival. Furthermore, it might also be important and helpful to highlight two factors that are responsible for why variation in many traits among humans today cannot anymore be considered under natural selection in the strict sense—due to the fact that humans have the capacity for empathy for others, and additionally (and unlike other animals that also have the capacity for empathy), due to the fact that we have culture and can therefore create conditions that do not create disadvantages for others (as an example the teacher could highlight the fact that she was

wearing glasses). Highlighting this aspect may be important especially in classrooms with diverse students (see also [73]).

Outside of the fields of science and evolution education, approaches to developing students' wellbeing and social–emotional competencies also exist that in fact integrate evolutionary concepts. For example, learning about emotions and ways to regulate them is usually a topic considered outside of the domain of evolution or science education (e.g., in the German primary school curriculum, the theme of emotions is situated in the subject of Ethics). However, such lessons can be enhanced with evolutionary concepts—such as exploring concepts of emotion in other (related) animal species or the functions that emotions have for animals and for our own everyday lives and well-being. In this regard, ref. [74] developed and evaluated a science education intervention for fourth-graders to promote "compassionate attitudes towards animals through gaining an understanding of their needs, emotions, capacities, current situations and their similarities with humans", and highlighted that "science education with a focus on promoting understanding and compassion towards animals could contribute to the amelioration of aggression in schools". Furthermore, a glance at primary school teaching materials about emotions showed potential for highlighting evolutionary concepts. For example, philosophical questions such as "what if there were no emotions [fear, anger, sadness . . .]" can be used to highlight the functions of emotions. The instructional strategy of stories about the natural selection of traits (e.g., [51], see Table 1) can be employed to develop stories about the natural selection of certain emotions. The Pixar movie *Inside Out* [75], developed in collaboration with the (cross-cultural, developmental, and evolutionary) psychologist Dacher Keltner, has also spurred a range of teaching materials that help to highlight the functions of emotions and their interactions with language, identity, and well-being, which can serve as vehicles to reinforce understanding of evolutionary concepts.

Some materials and approaches for encouraging health-related behavior also imply the use of evolutionary concepts. In the German framework for *Sachunterricht*, under the theme of health, we find an example lesson in which students compare the lifestyle and healthy behavior of humans in the stone age with the lifestyle and healthy behavior of children in the modern world, with the aim to help students understand and develop healthy behaviors such as exercise and diet ([18], p. 146). This lesson implicitly uses the concept of evolutionary mismatch as a teaching moment to motivate behavior change (see also [76,77]). Evolutionary mismatch can be defined as "a negative consequence that results from a trait that evolved in one environment being placed in another environment" [78]. However, this concept itself is not made explicit (to teachers or students) in the material. Teachers and students are thus not enabled to use this lesson in order to develop a more abstract and transferable understanding of this phenomenon which they could then use to understand many other potential instances of evolutionary mismatch that might impact human well-being and sustainable development in today's world [79–82].

In the EvoKids textbook by [40], another important possible instance of mismatch in our species is implicitly explored within the unit on human and cultural evolution. The text points out the role of group life, group cognition, and group markers in the evolution of our species, relates this aspect to students' own experience, and then asks the simple question "Are these things an advantage or could they also be dangerous?" (p. 99). Through this reflection, an understanding can emerge that our evolved group-thinking may lead to problems such as social conflict today.

These existing lesson materials served as an indication that the concept of mismatch might be productively integrated in the module design towards the discussion of a variety of instances of potential mismatch in our species and ways to overcome them.

A further approach that integrates evolutionary concepts and aims to enhance student mental health is the DNA-V model developed by [83]. It is based in the field of contextual behavioral science, which integrates interdisciplinary evolutionary theories towards an understanding of human cognition and behavior and the development of methods that enhance human flourishing [84]. Central within contextual behavioral science is the view of

individual learning and behavior change as evolutionary processes through mechanisms of variation and reinforcement, the view that due to language and symbolic thinking, humans can become "stuck" (often framed as an instance of possible mismatch) and thus need to be supported to rediscover and practice processes of mindful and flexible behavior change in service of their self-identified values.

The DNA-V model has been developed specifically for younger people to help them distinguish and practice different skills of their mind towards the development of psychological flexibility: the Discoverer stands for the skill of flexible behavior change as a source of behavioral variation; the Advisor stands for our "inner voice" which is shaped by past evolution and experience and may give helpful or unhelpful advice (related to the concept of mismatch); Values are like "selection pressures" for those kinds of behaviors that serve valued living; and the Noticer stands for the skill of mindful awareness of all these experiences. Hayes and Ciarrochi ([83], pp. 54–56) propose an activity about the evolutionary origins and functions of human language (our Advisor) and its negativity bias (i.e., our inner voice is often negative and warning us of potential problems). The activity shares elements with natural selection stories [51] by integrating variation, function, differential reproduction, and inheritance over many generations. Similarly, the well-being curriculum for students aged 4–11 by [85], informed by the DNA-V model, uses images of cave men and questions to help children understand the evolutionary origins and functions of emotions, language, and thoughts.

Such instructional methods focusing on the evolution of traits relevant to social-emotional learning may contribute to both conceptual understandings of evolution and psychological flexibility. Refs. [86,87] propose further activities and instructional methods based on contextual behavioral science that were integrated in the module design as related to the integration of evolutionary concepts.

Thus, this synthesis (summarized in Table 2) revealed that, besides the growing body of literature and collective PCK for teaching evolution in primary school *science* education, more and more opportunities exist to weave the teaching and learning of evolutionary concepts across a diversity of themes in the primary school curriculum, including towards the development of social–emotional learning. Most of these opportunities have not yet been explored by educational research regarding the development of primary student conceptual understanding of evolutionary concepts. However, we hypothesized that these expanding curricular connections can contribute to teacher motivation, positive attitudes, and interest for teaching evolution in primary school. These emerging opportunities thus represent another core rationale for this design study.

Table 2. Opportunities and innovations regarding the teaching of evolution across the primary school curriculum beyond natural science.

Themes, Concepts	Instructional Materials and Methods	Subject Connections	References
Evolution of human ability for running	Comparison of human skeleton and chimpanzee skeleton; Activity: jump up and down and notice which parts of the body (muscles, joints) are involved	Sports, health	Based on [88]
Evolution of human ability for throwing	Comparison of human skeleton and chimpanzee skeleton; Activity: Pretend to throw something and notice which parts of the body (muscles, joints) are involved; try to throw without turning your shoulders and without using your butt (like a chimp)	Sports	Based on [89]

Table 2. *Cont.*

Themes, Concepts	Instructional Materials and Methods	Subject Connections	References
Evolution of human skin colors	Children's book "The skin we are in"	Ethics, social studies, geography, history, social–emotional competencies	[90]
	Reflections about relation between skin color and health: Why do some some people need sunscreen; Why do some people suffer from vitamin D deficiency	health	Based on [91,92]
(Evolution of) cooperation/ cooperative behaviors	Cooperation games, e.g., Stone age hunt game; puzzle game	Social studies, social-emotional competencies	adapted from [71]
	Story of natural selection of cooperative groups in human evolution	History, social studies, social-emotional competencies	adapted from [51]; based on [93]
	Exploration of the function of our sense of fairness	Social studies, ethics	Variety of existing teaching materials
Cultural evolution (see also inheritance of traits, Table 1)	Sequential improvements of a design (e.g., paper planes) over successive generations of trial and error, selection, and transmission	Science (engineering); social-emotional competencies	[40,65]
Evolution of teaching (and language)	Challenge of recreating an artifact without a teacher and/or without gestures and language (e.g., origami, knots, knitting, baking, etc.); similarities to the games of Chinese whispers, charades	Science (engineering); social–emotional competencies	based on [66]
Evolution and function of emotions	Emotions in other animals	Social studies, ethics, social–emotional learning	based on [74,94]
	Philosophical questions and stories: What if there was no [emotion X]?	Social studies, ethics, health	variety of existing teaching materials
	Stories about the origins/natural selection of an emotional trait (e.g., with origins of mammals)	Science, language	adapted from [51]
	Movie *Inside Out* and associated materials	Social studies, ethics, language, art, health	[75]; variety of existing teaching materials
	Emotional diary/audit—notice emotions and reflect on their causes and functions	Social–emotional competencies	[87]
Evolution and function of language and thinking	Role play of different ancestors with different kinds of (negative, positive) or no thoughts and their survival	Social–emotional competencies	[83]
	Pictures of cave men with dangerous animals around and reflection questions	Social–emotional competencies	[85]
Evolutionary mismatch	Explore living conditions of stone age ancestors and living conditions today and derive conclusions for healthy behavior (diet and exercise)	Social studies, history, health	[18]
	Explore the role of group life in the survival of our stone age ancestors, think about how we form, live in, and demarcate groups still today, and think about how this can cause problems today	Social studies, history, ethics	[40]
	Compare the function of language/thoughts in the life of our ancestors, and the possible negative consequences of language/thoughts for human well-being today	Ethics, language, health, social–emotional competencies	based on [83]
Learning/individual level adaptation	Explore changes during an individual's lifetime (morphology, growth, behavior change, etc.)	Science, math	based on [32,47]

In the following sections, we describe how these findings were integrated in the iterative development of a module design, addressing research subquestion b of the study,

as well as methods of formative evaluation during two module implementation cycles, addressing research subquestions c and d of the study.

3. Methods of Iterative Module Design and Evaluation

3.1. Context of Implementation

The module "Evolutionary Anthropology in the *Sachunterricht*" was developed and implemented by the first author, who had extensive expertise in the topic and development of teaching materials as well as experience in teaching the themes in secondary school as well as secondary school teacher education and professional development. However, the author had no experience teaching evolutionary concepts in primary school and pre-service primary school teacher education.

The module was implemented in two semesters in 2020/2021 at the University of Leipzig, Germany, as part of the study program for primary and special education teachers. The study program requires all pre-service primary school teachers to study towards the teaching of *Sachunterricht*, math, German, and a fourth selected subject. Teaching of evolutionary concepts was not yet integrated in the program. Nonetheless, the structure of the teacher education program provided this opportunity, because within the program, students can choose among a variety of thematic module alternatives, including modules focusing on education for sustainable development, school gardens, social studies, democracy, geographic perspectives, citizen science, etc. This module was thus an elective among several alternatives.

Across both implementations, 36 participants took part in the module (18 per implementation). All except two participants gave their consent for the use of data for research purposes (thus the number of students of the second implementation whose data is included in this study is 16), and no further approval by the university ethics advisory board was required for this research. All participants were female, reflecting the high percentage of female students in the program. In the first module implementation, participants were in their 2nd–4th semester of study. In the second implementation, participants were in their 5th–9th semester of study, and three participants were in the special education program (training to become a teacher in a special education school or for supporting students with special needs).

3.2. Module Design

The module was designed to develop pre-service primary school teachers' CK and PCK, as well as attitudes, motivation, interest, and confidence to integrate the teaching of evolutionary concepts across contexts. The module design thus aimed to highlight that: evolutionary concepts are implicitly or explicitly already found across the curriculum and existing teaching materials; evolutionary concepts can be integrated and taught with a variety of active, age-appropriate methods; and evolutionary concepts can connect to everyday experience and aspects of social–emotional competencies.

Towards these aims, the initial module design was developed by adhering to the following initial design propositions, informed by general learning and instructional design theories [9,10,95] as well as the informal literature review as summarized in the previous sections:

1. Activate prior knowledge and focus on conceptual learning and transfer of learning:
    a. Highlight a core list of evolutionary concepts throughout (time and change, family relationships and common descent, trait, variation, function, inheritance, adaptation/adaptedness, environment, selection—natural, sexual, artificial; mismatch and negative consequences);
    b. Encourage reflection and discussion on pre-conceptions and co-construction of understanding (e.g., what is evolution, what is culture, what is an emotion, what is mismatch, what makes us human);
    c. Highlight and practice application of concepts across a diversity of contexts, including reflection and discussion on how evolutionary concepts can be ap-

propriately and critically transferred across domains (e.g., biological evolution, cultural evolution, genetic and cultural inheritance, individual and population-level adaptation, learning);

2. Explicitly integrate research of teaching evolutionary concepts to primary school students and a diversity of available materials and instructional strategies to develop foundational PCK;
3. Connect to the fullest possible range of curriculum themes and goals of the *Sachunterricht* and other subjects—expand the application of evolutionary concepts from natural to social/cultural, historic, and technological themes and to existing materials and methods of the *Sachunterricht*; as well as to social–emotional learning aims (often most situated in the curriculum standards of the subject Ethics in Germany), math, arts, sports, and language, to develop interdisciplinary PCK;
4. Make room for critical discussion and reflection of existing approaches and materials, especially regarding social–emotional learning goals;
5. Create opportunities for participants to practice the application of concepts and strategies to novel, participant-selected contexts through appropriate assignments.

These design propositions were considered to help foster the development of participants' positive attitudes and motivations to include evolutionary concepts in their teaching, as well as the various aspects of their interdisciplinary PCK (knowledge about core evolutionary concepts, curriculum goals, student conceptions, and instructional methods across traditional subject area boundaries).

The module followed local examination requirements and thus workload and assessment methods differed between the two module implementations. In the first module implementation, 1.5 h instruction time over 12 weeks was available, and assessment consisted of a written essay at the end of the semester in which participants chose a topic of interest to develop a lesson plan and integrate themes and methods explored in the module. A rubric was developed that evaluated the essay according to core aspects of PCK (based on [23] and adapted from [96], see also data collection and analysis methods below). In the second module implementation for advanced students, 3 × 45 min of instruction time over 15 weeks was available, and assessment consisted of a portfolio as well as a final group project. In both semesters, module implementation was in the form of digital online learning with synchronous and asynchronous components due to the COVID-19 pandemic. All synchronous meetings were held as video conferences, all assignments and materials were made available on the university learning management system (Moodle), and group discussions were documented in shared documents and discussion forums.

Overall, the module content was divided into several units, from building foundations in the first unit, towards applications to human evolution, and finally the application to social–emotional competencies (Table 3). In this regard, selected themes in the second and third unit were also considered to help develop or reinforce participants' pedagogical knowledge and own social–emotional competencies.

Table 3. Overview of module units and content.

Unit	Content	Rationale
1—Introduction and foundations	Core concepts of evolution and related aspects of PCK, focusing on application to plants and animals	This forms the basis of developing participants' PCK and integrates the educational research literature and existing materials.

Table 3. *Cont.*

Unit	Content	Rationale
2—Human evolution	Application to human evolution, with a focus on the evolution of human traits that connect to curricula, everyday experience, health, and social–emotional competencies: morphology, running and throwing (connection to sports, health), skin color (understanding of human diversity); cooperative hunting; tool making, teaching, social learning and childhood; culture and cultural evolution; and domestication (connection to school gardens); religion was added in the second module implementation (connection to subject of religion and addressing concerns about religious objections)	Concepts and the explored instructional strategies are applied to our own species, fostering participants' transferable understanding, connections to more diverse curriculum aims, and approaching social–emotional learning. Furthermore, some themes were considered to reinforce participants' pedagogical knowledge (teaching, learning and childhood), as well as their own social–emotional learning.
3—Social–emotional competencies	Application to themes related to social–emotional competencies: emotions; mismatch; learning; DNA-V Model (language and thoughts, mindfulness, flexible behavior change, values); cooperation	Concepts and instructional strategies are applied to social–emotional competencies, further fostering participants' transferable understanding and connections to more diverse curriculum aims. These themes were also considered to reinforce participants' pedagogical knowledge (evolution as learning, functions of emotions), as well as their own social–emotional learning.

Across both implementations, the module structure, content, and methods varied slightly. This was partly due to the changing context (available time and examination requirements), and partly due to considerations of module improvement after the first implementation as well as new insights resulting from the literature review. For example, in the second module implementation, the concept of learning progressions [21,32] was included to further reinforce the idea of weaving evolutionary concepts across the curriculum and grade levels. After the first module implementation, it became clear that a stronger focus on foundational content knowledge was necessary, since some participants in their final essays showed signs of misconceptions of certain concepts. Therefore, another design consideration was added:

- Include checks of content knowledge throughout the module as formative assessment tools.

To implement this design element, selected questions from the KAEVO2.0 evolution assessment questionnaire [27] as well as from [97] were used as teaching and formative assessment tools (informed by [98]).

The greater amount of time available in the second module implementation also allowed for the exploration of more themes. After the first module implementation, some students showed misconceptions about the concept of sexual selection, so this theme was included. In order to highlight the potential diversity of additional themes while also not overloading the module content, themes were to be explored selectively in a self-directed

way. This aspect also further helped to implement the design consideration 3 above (connect to the fullest possible range of curriculum themes and goals).

Given the increased need for online learning in education due to the pandemic and in order to allow participants to practice the creation of (online) activities before their final group project, an assignment was included that involved the creation of interactive online activities during the module on a selected theme.

The possibility of a portfolio in the second module implementation was also considered a strength, since it allowed a more regular and stringent documentation of participant learning and reflection compared to the final essay assignment of the first implementation. The implementation of the portfolio followed best practice guidelines [99] which were made explicit to participants in order to strengthen pedagogical knowledge about portfolios as formative assessment options even in the primary school context. The portfolio assignments consisted of: the creation of four consecutive mind maps or concept maps over the course of the module around the theme of evolution; answering PCK-related reflection questions around three participant-selected weekly topics of the module; the creation and reflection of a quiz for peers for one of the weekly topics; the creation and reflection of a digital learning activity for primary schools students for one of the weekly topics; sharing and peer feedback of portfolios and challenges mid-semester; reflection of the project group work; a final reflection at the end of the module, and a self-assessment of the portfolio with the help of a rubric.

Finally, the second module implementation included project group work in groups of 4–5 participants, so that lesson plans were developed in groups and presented to peers with discussion and feedback.

A more detailed syllabus and materials of the final module design can be found in the Supplemental Materials (Additional File S1).

3.3. Data Collection and Analysis for Formative Module Evaluation

To document challenges and opportunities during module implementation, participant CK and PCK, as well as attitudes, motivation, interest, and confidence towards the teaching of evolution (research subquestions c and d related to formative evaluation of the module), a variety of qualitative and quantitative data collection methods was employed: observation notes of video conferences and discussions; participant artifacts (notes on shared group discussion documents, assignment submissions, essays, portfolios); polls and questionnaires. Except for observation notes, data collection methods were integrated in the module design as teaching tools as well as formative and summative assessments. Table 4 summarizes data collection methods across both module implementations that we present and draw on in this article. A more detailed summary of methods across both module implementations can be found in the Supplementary Materials (Additional File S2).

Table 4. Overview of selected data collection methods discussed in this article.

Method	1st Module Implementation	2nd Module Implementation
Methods to assess participant preconceptions and attitudes		
Preconceptions on teaching evolution in primary school	Poll during video conference (N = 19) * Group discussion with worksheet	Moodle questionnaire (N = 19) *
Methods to assess participant content knowledge (CK)		
History of life milestones estimates on 1 m timeline	Screen annotation tool during video conference	
Polls regarding assessing tree thinking		Polls during video conference (week 3 and week 9)
Cultural evolution analogy table	Small group activity with worksheet	
Reflection on the concept of evolutionary mismatch		Small group discussions with worksheet

Table 4. *Cont.*

Method	1st Module Implementation	2nd Module Implementation
Examples of possible mismatch in humans	Small group discussions with worksheet	
Methods to assess participant pedagogical content knowledge (PCK)		
Story about the natural selection of a trait	Moodle database entry (N = 9)	Moodle glossary entry (N = 4)
Participant created lesson plans	Individual essay (N = 17)	Group work (N = 4)
Methods to assess module design and participant attitudes, motivation, confidence		
Mid-semester module feedback (week 8)		Moodle questionnaire (N = 10)
Final reflection (insights, challenges, confidence)	Small group discussions with worksheet (N = 5)	Portfolio assignment (N = 16)

* The numbers of participants were higher in these methods at the beginning of the semester because some students dropped out.

At the beginning of the semester, participant attitudes and preconceptions regarding the teaching of evolution in primary school were collected with the help of questionnaires and group discussions. Participants were asked to rate their agreement on questions such as "The word evolution does not appear in the curriculum. So we also shouldn't teach about it" and "The theme of evolution is too abstract and complex for primary school". Participants were also asked to rate the degree to which they think that evolution plays a role in the different perspectives of *Sachunterricht* as well as for the development of social-emotional competencies in students.

To assess participant CK, several assessment methods were used based on the KAEVO2.0 instrument [27]. For example, in both module implementations, a simple timeline activity was used to probe participants' general conceptions of deep time. On a timeline from the beginning of the earth until today represented on one meter (or rather, on a slide), participants were asked to mark (with annotation tools) the time for the estimated beginning of life, the time of the existence of dinosaurs, and the beginning of humans. In the second module implementation, quiz questions and polls targeting tree thinking based on the KAEVO2.0 and [97] were included. One question item was implemented again a few weeks later to check for learning. CK on various other concepts, including cultural evolution and mismatch, was assessed and documented through worksheet activities and observation notes of group discussions.

Participant PCK was assessed through the analysis of assignments and created artefacts. One assignment across both module implementations consisted of the creation of short stories about the natural selection of a trait. These were summarized regarding story themes and instances of possible misconceptions. A final assignment across both module implementations was the creation of lesson or unit plans on a topic of choice. A total of 17 lesson plans were created by individual or pairs of participants in the first module implementation, and four lesson plans were created by participant groups in the second module implementation. The lesson plans of the first module implementation functioned as the main summative assessment of the module and were thus also rated with the help of a rubric integrating components of PCK (based on [23,96]). All lesson plans were also thematically analyzed for the PCK elements of integrated topics and instructional strategies, and typologies of lesson plans were formed based on the PCK assessment and thematic analysis.

To assess participant evaluations of module design as well as their attitudes, motivation, and confidence, several feedback and reflection methods were used. A mid-semester feedback survey was used in the second module implementation to gain insight into how participants rated content, instructional methods, and workload of the module. In both module implementations, final reflections (group discussion or portfolio assignment) were used to gain insight into general attitudes of participants regarding the module content

and methods as well as their motivations and confidence in using presented materials and strategies in their future teaching. Questions included "Describe three-five most important insights that you gained from this seminar" and "What challenges do you see in implementing the ideas of this module in your future teaching?" Participants were also asked to rate and explain their perceived confidence in teaching evolutionary concepts in the future after taking part in the module. Responses were analyzed through thematic analysis to identify challenges and opportunities of module design and implementation, participant attitudes, motivation, interest, and confidence for the teaching of evolution, and other inductively emerging themes. Note that while the constructs of teacher attitude, motivation, and interest, as well as related constructs such as enthusiasm, are variously differentiated from and related to each other by some authors (e.g., [100,101]), for the purpose of our thematic analysis of qualitative data we group them together into one overarching theme (see also [102]).

4. Results of Module Implementation and Formative Evaluation

Addressing research subquestions 3 and 4 regarding formative evaluation of the module design, here we summarize selected insights from both module implementations regarding the development of participant CK, PCK as well as attitudes, motivation, interest, confidence, and associated implications in terms of challenges and opportunities, across various data collection methods (see Table 4). Given the exploratory nature and small sample size of our study, we follow recommendations by [103–105] and provide quantitative and semi-quantitative information of qualitative data when this serves to highlight general patterns and helps to support our conclusions, and we highlight that these patterns can not necessarily be generalized beyond our sample. All qualitative data that is described here has been translated from German into English. Where qualitative data is quoted directly, we provide the participant codes in parentheses (unless responses were anonymous).

4.1. Participant Preconceptions Regarding the Teaching of Evolution in Primary School

Results of the questionnaire and discussion at the beginning of the semester indicated that participants had generally positive attitudes regarding the teaching of evolution in primary school (see Supplementary Materials, Additional File S3, Figure S1). For example, most participants did not agree or not agree at all that evolution should not be taught because it does not appear in the curriculum. Furthermore, many participants considered evolution to connect to not just natural but also social, technical, historic, and geographic perspectives of *Sachunterricht* as well as social–emotional learning (see Supplementary Materials, Additional File S3, Figure S2). The same questionnaire was administered at the end of the module in the second implementation; however, not enough participants answered the questionnaire in order to derive any meaningful conclusions regarding changes in knowledge and attitudes.

4.2. Insights into Participant Content Knowledge

4.2.1. Tree Thinking and Deep Time Thinking

Participants' estimates on the timeline activity varied widely and results are similar to those reported in [27]. In particular, the existence of dinosaurs was estimated by most participants in the first third to half of the history of earth, and the origins of humans was estimated by many to be much earlier than the scientifically accurate time (see Supplementary Materials, Additional File S3, Figure S3).

Many participants had challenges correctly interpreting the relationships depicted in evolutionary trees (see Supplementary Materials, Additional File S3, Figures S4–S6). One question item was implemented again a few weeks later to check for learning (see Additional File S3, Figure S7). Results and ensuing discussions indicated that almost all (12 out of 13) participants were able to correctly interpret the relationships depicted in evolutionary trees, indicating that participants were able to easily overcome the initial

challenge of reading evolutionary trees through the formative assessment and discussions in the module.

Overall, deep time and tree thinking were often mentioned in the final reflections (see Section 4.3.2) as the concepts where participants felt uncertainty, presumably because the module made them aware of their misconceptions.

4.2.2. Conceptions about Cultural Evolution

Themes in human evolution were explored in the second unit of the module (seeTable 3 above). This included the exploration of culture and cultural evolution. In the first module implementation, participants worked in groups to fill out an analogy map comparing biological/genetic evolution and cultural evolution by the evolutionary concepts and processes of variation, selection, and trait transmission. Results indicated that participants were able to identify relevant and appropriate processes and mechanisms of trait variation, selection, and transmission across both domains, in a similar way as secondary pre-service and in-service teachers according to the authors' experience. This ability might represent a novel aspect of CK in relation to evolutionary understanding across biological and cultural domains. Of course, it is not expected that primary school students should be equally able to engage in such more abstract comparisons between biological and cultural evolution. At the same time, as highlighted above, existing resources for primary school such as Graf and Schmidt-Salomon [40] already target the learning goal of describing differences between biological and cultural evolution. Our results indicate that primary school teachers can develop the necessary CK regarding cultural evolutionary processes in order to integrate and capitalize on these teaching materials.

4.2.3. Conceptions about Mismatch

In the second module implementation, participants were engaged in an activity to derive or construct the meaning of the concept of evolutionary mismatch based on the example lesson of GDSU [18] highlighted above, which compared the lifestyle of stone age ancestors with today's lifestyle to derive implications for healthy behaviors. All groups were able to construct scientifically appropriate descriptions such as "an earlier adaptation that has lost its original purpose" and "my adaptation does not fit with the changed environmental conditions anymore". In another activity, all participant groups were also able to derive a range of possible instances of mismatch in our species similar to those discussed in the scientific literature [79–82].

4.3. Insights into Participant Pedagogical Content Knowledge

Here we summarize core insights into participant pedagogical content knowledge based on qualitative data from module assignments and observation notes.

4.3.1. Stories of Natural Selection

Within the theme of trait function, adaptation, and natural selection (see Supplemental Materials, Additional File S1), the instructional strategy of stories, based on [51] and [52], was introduced to participants. In order to practice the use of this strategy across contexts, participants were asked to create a story of the natural selection of a trait in a species of their choice, using the concepts and structure provided. Across both implementations, 12 stories were created and shared on the learning management system (not all participants created stories since it was not a requirement). Stories covered a diversity of contexts: elephants and big ears, giraffes and long necks, arctic hares and white fur, owls and their ability to turn their heads, spiders and their number of legs and eyes, hedgehogs and spines, grasshoppers and their ability to jump, horses and hoofs, mosquitoes and their buzzing. Many stories went beyond the minimal structure and included more creative story elements. Overall, most (10 out of 12) stories showed that participants were able to integrate the concepts of (random) trait variation, function, natural selection, and change over generations into their stories in such a way that they can be considered appropri-

ate vehicles for reinforcing population and selectionist thinking in their students. The instructor commented on a few problematic framings including: "One day, by chance, some elephants were born with very big ears". (W-12)—with continuous traits like ear size, it is problematic to speak of suddenly appearing large differences, and it is more appropriate to speak of small variations (which can accumulate over generations); "nature gifted some hares with a lighter fur" (W-15)—such framing should be avoided as it might reinforce intentionalist design thinking (god and/or nature as designer) and it is better to emphasize random appearance of variation and selection by environmental conditions; "some spiders that lived in caves, don't have eyes anymore because they didn't need them and thus the eyes regressed [German: *zurückbilden*]" (W-1)—this indicates and reinforces the misconception that morphological traits develop purely through use or disuse, and a better framing was proposed that included random variation, eyes' lack of function for survival and thus lowered selection pressure for eyes. In future module design, the critical peer-evaluation of participant stories could be more strongly integrated to develop and formatively assess PCK.

4.3.2. Applications to Themes in Social–Emotional Learning

The module design included several group discussions regarding the implications of concepts and instructional strategies for social–emotional learning and ways to overcome them. Regarding the exploration of variation in class, participants discussed pedagogical issues (see Section 2.4.2) and many ideas were collected by participants for dealing with them, including to carefully select which traits to use in comparison (e.g., eye color, hand span, [22]), also highlight similarities among all students, to include the teacher in the comparison, to highlight the value of diversity, or to instead explore variation among plants in the school garden or in animals.

4.3.3. Participant Created Lesson Plans

Seventeen lesson plans were created by individual or pairs of participants in the first module implementation, and four lesson plans were created by participant groups in the second module implementation. Lesson plans were targeted at grades 2–4, ranged in length from 2 × 45 min to two project weeks, and covered a wide diversity of topics.

Overall, participants were able to sufficiently integrate and demonstrate components of PCK in their lesson plans, including reference to appropriate and diverse curriculum learning goals in relation to their lesson, reference to student prior knowledge and understanding, and integration of appropriate teaching strategies and evaluation methods. The weakest component was the theoretical treatment of the concepts and of the relevant evolution education research literature in the lesson plans (Additional File S3, Figure S8).

Through assessment with the help of the PCK-informed rubric and thematic analysis several overlapping types or profiles of lesson plans could be identified (Table 5, Additional File S3, Figure S9).

Table 5. Types of participant-created lesson plans.

Type	Description	No. of Lesson Plans *	Examples and Comments
Foundational	Lesson plans on core evolutionary concepts and themes, integrating existing materials	11	Many of these lesson plans integrated resources such as [16,40,44]
Evolutionary concepts touched on	Only integrated a few evolutionary concepts or none	5	• A lesson plan on horses that only integrated phylogeny • Two lesson plans on emotions that did not integrate any evolutionary concepts

Table 5. *Cont.*

Type	Description	No. of Lesson Plans *	Examples and Comments
Inspired, creative	Lesson plans that included newly designed materials such as stories and worksheets, a variety of media, and integrating novel themes and ideas from the module	14	• Lesson plans that included self-created stories about natural selection or domestication • A lesson plan that modified vignettes from [46] to develop understanding of biologically and culturally transmitted traits • A lesson plan on human evolution that integrated cooperation and language • A lesson plan on the domestication of dogs with a created story and activities on dogs' senses and their functions for humans • A lesson plan on leaf cutter ants as an example of agriculture and coevolution, with comparison to human agriculture
Misconceptions or problematic content knowledge	Lesson plans that showed signs of remaining misconceptions or lack of deeper understanding of evolutionary concepts, or framings that might reinforce misconceptions in students	6	• A lesson plan that showed wrong understanding of sexual selection ("sexual selection is different because it is more about reproductive success and less about survival") (W-10) • Lesson plans that had problematic framings of adaptation ("plants also learned to adapt to their environments") (W-7)

* The numbers do not add up to the total of 21 lesson plans, because some lesson plans were coded for several categories.

One noteworthy profile was that of "evolutionary concepts touched on" which were lesson plans that integrated evolutionary concepts in a more or less tangential way. For example, one lesson plan was about the topic of horses, and included an activity in which students explore the ancestral species of today's horses, when they lived and their traits. The lesson plan did not integrate other evolutionary concepts that might be connected to the topic, like phylogenetic trees or adaptation and natural selection. However, this does not necessarily mean that these lesson plans were considered unsatisfactory, because after all, the learning goal was for participants to integrate evolutionary concepts across themes. These lesson plans in fact rather represent what it might look like to not treat evolution as an isolated topic in the curriculum but as a lens with which "nothing in biology makes sense". Two lesson plans in this category were about emotions, and while the evolutionary origins and functions of emotions were discussed in the theoretical section, the lesson plans and activities did not integrate evolutionary concepts at all, and this would be considered a less satisfactory outcome of the assignment in terms of PCK (but a positive development in terms of CK). In the second module implementation, lesson plans were presented to peers and discussed. This allowed one group, whose lesson plan about emotions did not integrate any evolutionary concepts (and could thus be categorized as "evolutionary concepts touched on"), to include several ideas into their final lesson plan about how to integrate functions of emotions today and in the past into their instructional strategies.

All four lesson plans of the second module implementation could be put into the category "inspired, creative", which might be partly due to the fact that the participants were more advanced in their study program, that the work in group instead of individually made them more motivated and "adventurous" to work on interesting themes and methods, that during the module they were required to practice developing an online learning activity

(online tools were integrated in several lesson plans), and that they were able to present their lesson plans in the class and discuss ideas for improvement, which were then integrated into the final lesson plan.

The lesson plans that indicated remaining misconceptions or superficial knowledge lead, in the second module design iteration, to more emphasis on checking for an understanding of foundational concepts, as well as the more explicit inclusion of the topic of sexual selection.

In future module designs, it would be beneficial to allow formative peer discussions and peer and self-evaluations towards improvement of participant created lesson plans (including lesson plans that were created by previous cohorts) especially regarding the appropriate integration of evolutionary concepts and other elements of PCK (e.g., [106]).

4.4. Insights into Module Design and Participant Attitudes, Motivation, Interest, and Confidence

Here we summarize insights into participant evaluations of module design, participant attitudes, motivation, or interest as well as reported confidence for teaching evolution in primary school, based on mid- and post-reflection and feedback surveys, and we highlight implications regarding module design.

4.4.1. Participant Evaluations Based on Mid-Semester Feedback and Final Reflections

Responses from mid-semester and final reflections gave insights into the evaluations and suitability of certain instructional design elements of the module. In the mid-semester feedback survey, participants (N = 10) rated the content as very interesting and positively evaluated the digital format, the group work, portfolio assignments, and the overall workload. Some participants rated the content as rather advanced and a few rated the content as not very relevant for practice (see Additional File S3, Figure S10–S12). Qualitative responses in the mid-semester survey further indicated participant satisfaction with content and with the instructional methods and digital format. Participants mentioned the variety of methods, the diversity of content, the ability to exchange in groups, and digital implementation, with comments such as: "The content also speaks to me very much; because current studies, interesting illustrations and exciting facts are always included"; "I've been really happy so far. I find the content very, very exciting and I think it's really nice how it was prepared for us. . ."; "I like the group work, surveys, the varied methods between Zoom meetings and asynchronous work. The choices between the topics!!!"; "I find it very interesting and the mixture of technical information and the reference to elementary school is really great. But above all I think the materials that you also make available are great, because you can then fall back on them in practice"; "I think it's very good that we get many opportunities to exchange ideas in groups", "If there's an opportunity for an interesting online learning that doesn't get boring and that one still looks forward to every week, this is it. This has been my first seminar for a year and a half, which I enjoy doing again and which I am looking forward to. The first seminar in which I also feel integrated. I am very fortunate to be here and to see that digital teaching can also look like this". Several comments spoke to the need to delve deeper into the topics or the need to make more connections to the curriculum and to teaching practice, while others mentioned challenges with the breadth of content or with the portfolio assignments.

In the second module implementation, participants (N = 16) were asked to describe the three–five most important insights gained from the module. Thematic analysis revealed a number of general themes in participants' reflections: increased motivation and interest in teaching evolution; awareness about own misconceptions; increased general (P)CK; interest and increased (P)CK regarding themes of human evolution and social-emotional learning; and insights related to the materials and instructional methods of the module (see Supplementary Materials, Additional File S3, Figure S13).

Increased motivation and interest was apparent in statements like "Overall, I was amazed about how versatile this topic is." (S-5, S-15); "There was not one week where I did not come out with an 'Aha, Wow'. After the sessions I went to my friends and family and

proudly presented what I had learned (. . .) I found the topics incredibly fascinating and interesting. I'm excited to see when I can actually use evolution in science lessons and how the children will react to it." (S-8); "I have become aware of how well the theme of evolution can be integrated with all the perspectives of *Sachunterricht* and that it is also very suitable as an interdisciplinary topic. Before, I had never really dealt with the subject of evolution and I now see great potential for including it in interdisciplinary teaching." (S-1); "Before the seminar, I did not know the far-reaching role evolution plays in our lives. Evolution explains not only the origin of all living beings with their specific characteristics, but also our modern world. Evolution can thus help us to understand the current world. (. . .) the subject of evolution is very all-encompassing and directly and indirectly fundamental to many subjects in science education. I have learned that many issues can be looked at from an evolutionary perspective. In this way, students as well would come to better understand important connections early on." (S-9); "I became aware of how important it would be to integrate evolution/evolutionary anthropology as a solid component into the curriculum of the *Sachunterricht*." (S-16). One participant who declared that she was Roman Catholic stated "I also find the perspective of the theory of evolution on religions interesting. (. . .) One insight that was strengthened for me through this seminar is that religion and science are quite compatible and are not as opposed to each other as it might seem at first." (S-11). Some participants also mentioned several module design elements, such as the regular group discussions, the making available of a diversity of resources, and the implementation of the online learning format as helpful (see Additional File S3, Figure S13).

4.4.2. Participant Confidence and Perceived Challenges

In rating their perceived confidence in teaching evolutionary concepts in the future after taking part in the module, most participants across both module implementation felt "pretty confident" to "very confident", with confidence ratings increasing somewhat between module implementations (Additional File S1, Figure S14). In the explanations, a number of module design elements were mentioned that contributed to participants' confidence: the portfolio reflection assignments; the regular group discussions which helped clarify questions and concepts; the creation of an online activity; the creation of the consecutive mindmap; the final project work; the diversity of materials (including lesson plans, worksheets, books, videos), ideas and methods explored and made available on the learning management system; relevance of ideas for social–emotional learning and students with special needs. Some participants also remarked how the module sparked their interest and motivation to teach and learn evolutionary themes such that they spent more time exploring them on their own, were able to remember module content well, or thought about ways to implement them in their teaching, which contributed to their confidence. Many participants remarked that they still felt unsure in areas of their content knowledge. Some were made aware that they had misconceptions and difficulties which still needed to be overcome, especially regarding tree thinking and deep time, and they were worried to reinforce misconceptions in students. Some highlighted that they felt that many themes were covered only superficially and that they would have liked or needed more time to go deeper. Finally, some remarked that they are not sure about their ability to implement their knowledge in practice and to convey it to students, and they would have liked more opportunities to practice some of the methods in class (which was partly not possible due to the need for online learning). One participant also mentioned that their lack of confidence is related to the fact that the topics are not explicitly addressed in the curriculum and that she has not come across any examples during her practical school placements so she has never seen for herself what it looks like in practice.

Finally, participants across both module implementations were asked to describe challenges they see to implement themes and ideas explored in the module in their future teaching. Similar to themes emerging in the confidence ratings, described challenges related to the curriculum and available time, complexity of the topic and resulting uncertainties regarding didactic reduction, remaining uncertainties related to aspects of PCK (dealing

with misconceptions or religion, relative lack of materials compared to other topics), and implications for social–emotional learning of students with special needs. The most common challenge mentioned with nine occurrences was related to aspects of the curriculum in terms of difficulty to connect some themes (such as human evolution) directly to the curriculum and the lack of available time (see Additional File S3, Figure S15). In describing her challenge of dealing with religious beliefs, one participant remarked that "since the opinion of scientists and researchers also changes or can change, I don't think it's right to say that the current state of research is the only correct one and that possible religious beliefs should immediately be labelled as wrong." (S-15). This indicates a need for an increased emphasis on teaching the Nature of Science (NoS), especially the role of (un)certainty, probability, and continuous self-correction in science [107,108]. Others have remarked that these aspects of science are particularly important in evolution education [109]. Within the module, aspects of NoS were woven in, e.g., by emphasizing both the mounting evidence in general terms, plus inconclusiveness or disagreements among scientists regarding specific scientific findings (such as regarding the patchiness of the human fossil record and how to interpret individual fossil findings, theories about why Neanderthals went extinct, or whether animals can be said to have emotions). The role of uncertainty and openness to new findings in science was also emphasized within the (optional) theme of religion and science (it is unclear whether the participant who made the above comment explored this theme).

5. Discussion

This study aimed to explore whether a pre-service teacher education module can be designed that supports the development of participants' CK, PCK, as well as attitudes, motivation, interest, and confidence for teaching evolutionary concepts across the curriculum. This study added to the knowledge base by providing a review of collective PCK regarding the teaching of evolutionary concepts at the primary school level and integrating it into a module design for pre-service primary school teacher education. Furthermore, an innovation of the resulting module design lies in the stronger integration of themes beyond natural science, including human evolution, cultural evolution, cooperation, and social–emotional learning, thus advancing the development of interdisciplinary PCK for evolution. Through two cycles of module implementation and re-design, we explored the feasibility and effectiveness of this module design regarding participant CK, PCK, as well as motivation, attitudes, interest, and confidence regarding the teaching of evolution through a diversity of mixed methods. Overall, evidence indicates that the module positively impacted participants' interests and motivations to teach evolution in primary school, and that participants were able to develop foundational PCK around teaching evolution in primary school. Furthermore, it appears that several elements of the module design, developed based on theoretical design considerations, have positively contributed to these outcomes. However, this one semester module was not able to fully overcome some of the lack and uncertainties in participants' CK and PCK regarding the theme of evolution. In this regard, the module was also ambitious in terms of not only developing foundational CK and PCK regarding the teaching of evolution in primary school, but also in terms of its broadness of themes, going beyond applications to plants and animals, and into human evolution, cultural evolution, and social–emotional competencies. On the one hand, this may have been a weakness in terms of not allowing sufficient time to develop deeper participant (P)CK on foundational concepts, on the other hand, it appeared that the inclusion of themes on human evolution and social–emotional learning contributed to increased positive attitudes and motivations of participants regarding the theme of evolution and its teaching in primary schools. Furthermore, because evolutionary concepts are not explicitly integrated in the state curriculum, the motivation for this design study was to connect evolutionary concepts to a diversity of existing curriculum goals and themes. However, the module was also not able to fully overcome this systemic limit, with lack of time and lack of explicit curriculum integrations being the main challenge highlighted by participants.

It is clear that the context of this study was unique in terms of allowing the space for a full semester module within a primary teacher education program to explore the teaching of evolutionary concepts. This may not be feasible in all teacher education contexts. Additionally, it may not even be the most effective way to simply "single out" evolution in one separate, full-semester module. As some of the participant reflections indicated, there was remaining uncertainty because this module was the first time that most participants were exposed to even the possibility of teaching evolutionary concepts in primary school. Similar to the aspiration that evolutionary concepts should be woven into the school curriculum throughout, opportunities should be considered to weave evolutionary concepts into pre-service teacher programs. The ambitious breadth of the present module design might thus be more appropriately explored in its full potential by integrating selected aspects across different pre-service teacher modules (such as science education, social studies, health, and social–emotional learning).

In this regard, during module development and implementation, a number of insights and possible new teaching approaches emerged that have implications for general evolution education practice in primary school and beyond, including approaches to: appropriately deal with the exploration of variation in the classroom; counter genetic determinism by considering genetic as well as behavioral/cultural traits and their differing transmission mechanisms; explore the evolution of cooperation (especially in humans) and symbiosis, in order to not just focus evolution education on competition and predator-prey dynamics; explore the evolution of emotions and human language; and approaches to include the concept of mismatch in reflections on health-related behaviors (see Table 2). These may add to closing some of the gaps in collective PCK in evolution education for high school level identified by [30], such as on the themes of evolution of behavior, coevolution, and evolutionary medicine.

Overall, the current lack of an explicit integration of evolutionary concepts in the German *Sachunterricht* curricula remains one of the higher-level limiting factors. It is clear that curriculum development suffers from multiple demands and the resulting pressure of "curriculum overload" [110] such that priorities need to be set. However, this design study aimed to highlight how evolutionary concepts relate to a range of existing curriculum themes and can contribute to many learning goals in an integrated fashion. Furthermore, many themes explored in the module are found in subject areas beyond natural science, such as ethics, social studies, sports, or health. Given this potential together with the centrality of evolution in the sciences, we suggest future curriculum developers more explicitly integrate evolutionary concepts in primary school curricula, in Germany and beyond, to enable the development of a coherent and networked understanding of the natural and social world in (pre-service) teachers and students.

This study has a number of limitations regarding the generalizability of findings. Firstly, it can be presumed that there was a high degree of self-selection regarding the module participants, and that their attitudes towards the content of the module might not be representative of the larger pre-service primary school teacher population, at this university and beyond. At the same time, given the relatively positive attitudes towards teaching evolution in primary school among a group of UK pre-service teachers (almost half of which were religious) observed by [35], such a self-selection bias might not exist when it comes to attitudes towards the module content. Furthermore, despite the fact that participants voiced some concerns and uncertainty regarding religious objections to evolution, one participant studied to be a religion teacher, and one participant declared that she was Roman Catholic, religious objections were apparently not an issue in this participant group.

The module also had to be implemented in a fully online format. This hindered the opportunity to immerse participants in certain instructional strategies such as simulation games, modelling activities, handling of fossil replicas, the collective viewing and discussion of media, or visits to out-of-school environments and informal learning places like museums or the local zoo. Participant reflections indicated that this aspect might have

negatively affected some of their ratings of confidence in using the strategies in future teaching. Even though many activities can be implemented in an online format and the online implementation of this module was rated positively by participants, ideally, future implementations should allow a more place-based and hands-on immersion to increase pre-service teachers' competence and confidence.

Another related limitation is that this study did not explore enacted teacher PCK (sensu [24]), i.e., the actual practice of teachers implementing instructional strategies in the classroom and effects of this practice on student learning.

Furthermore, while a large part of teaching materials and strategies that were included in the module are based on empirical studies, a number of materials and instructional strategies remain unexplored in terms of their appropriateness and ability to achieve learning goals in primary school classrooms (including materials and instructional strategies that were newly developed during the module design). In particular, unexplored directions remain in the potential of materials and instructional strategies for developing transferable understandings of cooperation, cultural evolutionary processes, mismatch, or the potential reinforcing connections between the social–emotional learning that is targeted with DNA-V materials [83,85,86] and the conceptual learning of evolutionary concepts.

Future research might include the implementation of module elements across more diverse contexts (including those in which evolutionary concepts are more explicitly included in curricula); as well as a more structured and summative evaluation of CK and PCK, including enacted PCK, of participating pre-service teachers before and after taking part in such a module. However, regarding evaluation of CK and PCK, it is important to point out that no validated assessment tools are known to exist regarding understanding (and teaching) of evolution in relation to themes like cooperation and other social and behavioral traits, cultural evolution, and social–emotional learning (see also [30,111]).

The module syllabus and all materials resulting from this study can be accessed on the OpenEvo Moodle learning platform (see Supplementary Materials, Additional File S1). We invite others to implement elements towards the further design-based improvement and evaluation of this module or selected elements across contexts.

6. Conclusions

Despite the centrality of evolutionary theory in biology and increasingly in other disciplines, the mounting calls to teach evolutionary concepts early and across grades, as well as the increasing collective PCK about teaching evolutionary concepts in primary school, it is not yet a given that evolutionary concepts are explicitly included in primary school curricula. This demands design-based explorations of innovations to help resolve this problem and explore new learning potentials. The design study reported here aimed to explore the feasibility and effectiveness of a pre-service teacher education module regarding the development of participant CK, PCK, and positive attitudes regarding the teaching of evolutionary concepts across a range of themes in the primary school curriculum. The module design was based on general theories of learning and conceptual understanding and integrated a range of existing knowledge regarding teaching evolution in primary school, as well as novel ideas for integrating themes in human evolution and social-emotional learning. Initial evidence indicates that the module had a positive impact on participant attitudes and PCK. However, some participants were not able to fully overcome their gaps in CK and remained uncertain about implementing ideas in their future teaching. One area of concern was the fact that the local curriculum does not explicitly prescribe the teaching of evolution and thus not enough time might be available in the curriculum to fully exploit the potential of this theme. Nonetheless, novel design considerations and teaching approaches emerged in this design study that can be integrated into existing pre-service teacher education curricula.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/educsci13080797/s1: Additional File S1—Extended Syllabus of Final Module Design (pdf); Additional File S2—Data collection and assessment methods across implementations (pdf); Additional File S3—Results of questionnaires, polls, and content analyses (pdf).

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