Knowledge and Acceptance of Evolution in Europe – Empirical Findings of European Cross-Country Analyses

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Dissertation

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Abbreviations

Instruments

ACORNS: Assessing Contextual Reasoning About Natural Selection
ATEEK: Assessment Tool for Evaluating Evolution Knowledge
ATEVO: Attitudes Towards Evolution
ATEVO-EG: Attitudes Towards Evolution in General
ATEVO-EM: Attitudes Towards Evolution of the Human Mind
BCI: Biological Concepts Instrument
CANS: Conceptual Assessment of Natural Selection
CINS: Concept Inventory of Natural Selection
EALS: Evolutionary Attitudes and Literacy Survey
EALS-SF: Evolutionary Attitudes and Literacy Survey – short form
ECKT: Evolution Content Knowledge Test
ECT: Evolution Concept Test
EEQ: Evolution Education Questionnaire
EvoDevoCI: Evolutionary Development Concept Inventory
FACE: Framework to Assess the Coverage of biological Evolution by school curricula
GAENE: Generalized Acceptance of Evolution Evaluation
GeDI: Genetic Drift Inventory
I-SEA: Inventory of Student Acceptance of Evolution
KAEVO: Knowledge About Evolution
KAEVO-A: Knowledge About Evolution Part A
KAEVO-B: Knowledge About Evolution Part B
KAEVO-C: Knowledge About Evolution Part C
KEE: Knowledge of Evolution Exam
MATE: Measure of acceptance of the theory of evolution
MUM: Measure of Understanding of Macroevolution
ORI: Open Response Instrument
PERF: Personal Religious Faith
RaProEvo: Randomness and Probability Knowledge Test (context: Evolution)
SECM: Scales of Conflict with Evolution Measure

Statistical values

α: Cronbach's alpha
AIC: Akaike information criterion
ANOVA: analysis of variance
BIC: Bayesian information criterion
CFA: confirmatory factor analysis
CI_{95}: 95% confidence interval
EFA: exploratory factor analysis
Est.: Estimates
ICC: intraclass correlation coefficient
IQR: interquartile range
M: mean
N: total sample size

n:	sample size
PAF:	principal axis factoring
PCA:	principal component analysis
Q1:	Quartile 1
Q3:	Quartile 3
QQ-plots:	quantile-quantile-plots
r:	Pearson correlation
SD:	standard deviation
SE:	standard-error
X^2:	LRT results

Other abbreviations

BIOHEAD:	Biology, Health and Environmental Education for better Citizenship
e.g.:	for example
FOWID:	Research Group on Worldviews in Germany (Forschungsgruppe für Weltanschauungen in Deutschland)
ISCED:	International Standard Classification of Education
KiL project:	Interdisciplinary project named "Measuring the professional knowledge of preservice mathematics and science teachers" (Messung professioneller Kompetenzen in mathematischen und naturwissenschaftlichen Lehramtsstudiengängen)
MC:	multiple choice
NOS:	nature of science
TRAPD:	Translation-Review-Adjudication-Pre-test-Documentation
UK:	United Kingdom

1 Introduction

The *theory of evolution*, established more than 150 years ago by Charles Darwin and independently by Alfred Russel Wallace, provided the first scientific and naturalistic explanation for biodiversity, similarities among organisms, and many other biological processes. The *theory of evolution* builds a uniform basis for biology and enabled biology to become an independent science. Also, with the help of the *theory of evolution*, creation, as well as teleological and finalistic thinking have become redundant to explain the origin of species (including human evolution) and biological changes over time (Vollmer, 2017). Today, it is a scientific consensus that understanding the processes and concepts of evolution is essential to acquire scientific literacy and understand other biological processes and relationships (Nationale Akademie der Wissenschaften [Leopoldina], 2017).

Since the *theory of evolution* was published, it gets rejected by some groups of people. Today, the problem of people rejecting evolution is a worldwide issue, but it can vary greatly from region to region (European Commission, 2005; Gallup, 2017; Ipsos Global @dvisory, 2011; Miller, Scott, & Okamoto, 2006). Creationism in its various variants, the rejection of evolution in favor of a belief in creation, often plays a significant role in resistance to evolution (Scott, 2008).

In line with its importance, evolution is a central topic in science education research (Dunk et al., 2019). At the same time, research has repeatedly shown that students of different education levels all over the world struggle to understand important aspects of evolution (e.g., Beniermann, 2019; Graf & Soran, 2010; Harms & Fiedler, 2019; Champagne Queloz et al., 2017; Sbeglia & Nehm, 2018). These assessments are important to reveal the extent to which students understand/accept evolution and the reasons why they partially lack acceptance of evolution as well as knowledge about evolution. With the help of these insights, teaching strategies can be developed to promote acceptance of evolution as a scientific fact and evolutionary theory as its explanation. For example, these strategies might support learners to develop the competence to make sound judgments about the compatibility of evolution and religion (Barnes & Brownell, 2017; Barnes et al., 2021; Mead, Hejmadi, & Hurst, 2018).

With the growing interest in research on evolution knowledge and acceptance, an open discussion about their relationship arose (Barnes et al., 2019; Dunk et al., 2019; Glaze & Goldston, 2015), not least because of deviating results (e.g., Athanasiou, Katakos, &

Papadopoulou, 2016; Großschedl, Konnemann, & Basel, 2014; Trani, 2004). Barnes et al. (2019) contributed greatly to the investigation of these different results by showing that different instruments, which aim to measure acceptance of evolution, can lead to deviating results. Beniermann (2019) analyzed common evolution acceptance instruments (MATE (Rutledge & Warden, 1999), EALS (Hawley et al., 2011), I-SEA (Nadelson & Southerland, 2012), and GAENE (Smith, Snyder, & Devereaux, 2016) and revealed measuring issues influencing results gathered with these instruments. The construct *knowledge about evolution* comprises several underlying concepts, for example, adaptation, speciation, and heredity (Urry et al., 2019). Existing instruments that seek to measure knowledge about evolution differ in terms of the included evolutionary concepts (Mead et al., 2019). Therefore, the results of studies on knowledge about evolution, which used different measuring instruments, may be not comparable.

Numerous instruments exist for measuring acceptance of evolution (Beniermann, 2019; Hawley et al., 2011; Nadelson & Southerland, 2012; Rutledge & Sadler, 2007; Rutledge & Warden, 1999; Short & Hawley, 2012; Smith et al., 2016) as well as knowledge (Anderson et al., 2002; Beniermann, 2019; Bishop & Anderson, 1990; Kalinowski, Leonard, & Taper, 2016; Nadelson & Southerland, 2009; Nehm et al., 2012; Perez et al., 2013; Price et al., 2014; White, Heidemann, & Smith, 2013) and some lack evidence for validity and reliability, especially if the instrument has been modified or if it has been used in new populations (Mead et al., 2019). An instrument's lack of evidence for validity and reliability is an additional measuring issue that could lead to not comparable or misleading findings.

To date, most evolution education research has been conducted in the United States, possibly explained by the public resistance against evolution (Brenan, 2019). In Europe, the circumstances are very diverse due to different educational systems, languages, and more fragmented research communities (Harms & Reiss, 2019). A systematic literature review to examine the level of acceptance of evolution and knowledge about evolution as well as the data quality in Europe is still missing. In addition to that, there is no comprehensive overview of knowledge and acceptance in Europe, based on comparable data gathered with the same instrument.

This dissertation addresses these open research fields and provides new insights into the existing state of research of evolution education in Europe. In the following Chapter 2, the underlying theoretical background of this research is explained. The first section (Chapter 2.1) examines evolution as a construct that contains multiple underlying concepts. Following this (Chapter 2.2), different conceptions about evolution are introduced. Afterward, acceptance of evolution, its assessment, and influencing factors are discussed (Chapter 2.3). In Chapter 2.4, different instruments, which seek to measure acceptance of evolution or knowledge about evolution, are described. Taking up on this, different dimensions of measuring issues are discussed (Chapter 2.5), containing the missing definition of key constructs, the issue of the complexity of knowledge about evolution, and measuring issues in evolution acceptance instruments. The theoretical background will end with a description of evolution education research in Europe and its special obstacles (Chapter 2.6).

In Chapter 3, the overall aims of this dissertation as well as a tabular overview of the conducted research are presented. The following chapters (Chapter 4-6) consist of the published research papers. Conclusively, the final two chapters contain an overall discussion of the dissertation (Chapter 7) as well as implications for future research (Chapter 8).

2 Theoretical Background

2.1 Key concepts of evolution

The topic *evolution* consists of several underlying key concepts described in the literature (e.g., Futuyma, 2013; Tibell & Harms, 2017; Urry et al., 2019). It is important to understand these key concepts to gain comprehensive knowledge about evolution (Anderson, Fisher, & Norman, 2002; Gregory, 2009; Tibell & Harms, 2017). Subsequently, instruments that seek to measure *knowledge about evolution* comprehensively should contain these key concepts (see Chapter 2.4.1). In the following, the central key concepts to understand evolution are briefly described.

Individuals in a population vary in their hereditary traits, which is called variation. During the reproduction process, individuals pass on their genomes from generation to generation. This can be described as inherited variation (Urry et al., 2019).

Evolutionary adaptation, natural selection, and biological fitness are three closely linked processes. Natural selection means that individuals with certain hereditary traits can survive better than individuals without these traits in the same population and subsequently produce more offspring. Individuals that can produce more offspring than others in the same population have better biological fitness. Over time, this process leads to evolutionary adaptations of organisms to their environment. If the environmental conditions change, natural selection can result in new evolutionary adaptations to these new conditions (Urry et al., 2019).

A biological species comprises a group of populations with individuals that can potentially produce viable and fertile offspring if they interbreed. Speciation means that separated populations pass through evolutionary changes and subsequently cannot produce viable and fertile offspring with an individual of the other population anymore (Urry et al., 2019).

According to the state of research, the Earth exists for 4.6 billion years (Ogg, Ogg, & Gradstein, 2016). This period is called deep time (McPhee, 1981). The appropriate understanding of deep time is essential to develop a scientific understanding of evolution (Graf & Hamdorf, 2011).

2.2 Conceptions about evolution

Many evolutionary concepts, for instance, that evolution pursues no target or the enormous amount of time in Earth's history (the concept of deep time), are difficult to understand with our everyday thinking (e.g., Catley & Novick, 2009; Gregory, 2009). It has been shown that students develop pre-instructional ideas about evolution, based on their experiences in everyday life (e.g., Fiedler, Tröbst, & Harms, 2017; Nehm et al., 2012). These alternative conceptions (also called misconceptions, preconceptions, or naïve ideas; Graf & Hamdorf, 2011; Leonard, Kalinowski, & Andrews, 2014; Maskiewicz & Lineback, 2013) have an impact on the learning success of students, which is why science teaching should take these conceptions into account (Bishop & Anderson, 1990).

Alternative conceptions about evolution of students in all different education levels have been investigated for decades in science education research (Anderson et al., 2002; Bishop & Anderson, 1990; Graf & Soran, 2010; Gregory, 2009; Ha, Baldwin, & Nehm, 2015; Harms & Reiss, 2019; Kalinowski et al., 2016; Nehm & Reilly, 2007; Yates & Marek, 2014). It has been found that these alternative conceptions resemble each other between students (Gregory, 2009). Thus, typical alternative conceptions can be clustered into conceptions categories, to enable a systematic classification. These categories should also be part of the education of trainee biology teachers, as they struggle to identify their students' alternative conceptions categories (Fischer et al., 2021). In the following, widespread and recurring alternative conceptions about different evolutionary aspects are presented. These misconceptions have been discovered in studies around the world (detailed overviews have been created by Gregory (2009) and Harms & Reiss (2019)).

There is a large number of alternative conceptions in terms of evolutionary adaptation and natural selection. Teleological thinking or finalistic thinking is the idea that adaptation occurs with a purpose and is controlled by a higher authority or the organism itself (Bardapurkar, 2008; González Galli & Meinardi, 2011; Gregory, 2009; Rosenberg & McShea, 2008; Sinatra, Brem, & Evans, 2008). Persons who argue finalistic think that organisms adapt goal-orientated, following either their own goals or goals dictated by the environmental conditions. Students who argue anthropomorphic assign human characteristics onto animals, plants, or inanimate things (Fiedler et al., 2017; Gregory, 2009). In a Lamarckian argumentation, morphological traits, which the parent generation acquired or modified throughout their lives, are inherited (Crow, 2004; Gregory, 2009; Kampourakis & Zogza, 2006). Typological thinking is the idea that individuals of a species have the same main traits, or rather that different types exist within a population in which only little variation exists (Alters, 2005; Graf & Hamdorf, 2011; Gregory, 2009; Shtulman, 2006). According to Graf and Hamdorf (2011), the focus of typological thinking lies on the similarities of the individuals and minor variations are considered insignificant. Change without cause is a conception, which means that generation happens spontaneously (Brennecke, 2015; Evans, 2001).

However, apart from evolutionary adaptation and natural selection, alternative conceptions on other evolutionary aspects are also known. It is difficult for students to evaluate the role of chance and probability in evolution (Fiedler et al., 2017; Greene, 1990), to read and interpret phylogenetic trees (Phillips et al., 2012; Schramm, Jose, & Schmiemann, 2021; Schramm, Schachtschneider, & Schmiemann, 2019), to describe and interpret the term biological fitness (Beniermann, 2019; Bishop & Anderson, 1986), and to understand the dimensions of deep time as well as to classify events in the history of the Earth (Catley & Novick, 2009; Libarkin, Kurdziel, & Anderson, 2018).

2.3 Acceptance of evolution

Although evolution is the unifying concept of biology, it has been shown that a relevant number of people, also biology university students or teachers, reject evolution (European Commission, 2005; Gallup, 2017; Ipsos Global @dvisory, 2011; Miller et al., 2006). The assessment of the reasons why people refuse to accept evolution has come to the fore in the last decades with the most research conducted in the United States (Dunk et al., 2019). Awareness about these influencing factors on acceptance of evolution is the basis for fostering the acceptance of evolution and science in schools. It should be mentioned that serious measuring issues (see Chapter 2.5) of some common instruments that aim to measure acceptance of evolution have been revealed (Barnes et al., 2019; Beniermann, 2019), which is why conclusions on the state of acceptance of evolution as well as its influencing factors and especially comparisons between different study groups should be taken with caution.

Various influencing factors on acceptance of evolution are described in the literature, such as knowledge about evolution (Allmon, 2011; Akyol et al., 2012; Athanasiou, Katakos, & Papadopoulou, 2012; Cofré, Cuevas, & Becerra, 2017; Deniz, Donnelly, & Yilmaz, 2008; Graf & Soran, 2010; Großschedl et al., 2014; Ha, Haury, & Nehm, 2012; Lammert, 2012), attitudes towards science (Graf & Soran, 2010; Großschedl et al., 2014; Lammert, 2012), understanding of the nature of science (NOS; Allmon, 2011; Akyol et al., 2012; Athanasiou et al., 2012; Dunk et al., 2017; Graf & Soran, 2010), religiosity (Allmon, 2011; Athanasiou et al., 2012; Beniermann, 2019; Graf & Soran, 2010; Lammert, 2012), or contextual categories (Allmon, 2011; Deniz et al. 2008; Dunk et al., 2017; Großschedl et al., 2014; Ha et al., 2012).

However, the relationships of each of these factors with the acceptance of evolution are partly elusive. For instance, numerous studies have investigated the relationship between knowledge about evolution and acceptance of evolution with deviating results. Some studies revealed a positive relationship (e.g., Akyol et al., 2012; Buchan, 2019; Deniz & Sahin, 2016; Dunk et al., 2017; Großschedl, Seredszus, & Harms, 2018; Nadelson & Sinatra, 2009; Nehm et al., 2013; Stanisavljevic, Papadopoulou, & Djuric, 2013) while others stated that there is no relationship between those two constructs (e.g., Akyol, Tekkaya, & Sungur, 2010; Athanasiou et al., 2016; Sinatra et al., 2003; Tekkaya, Akyol, & Sungur, 2012). Sinatra et al. (2003) assumed that the knowledge about evolution has to reach a certain level before it influences the acceptance of evolution and Beniermann (2019) demonstrated evidence for this assumption by comparison of different sampling groups.

In summary, it can be said, that whereas the body of research is solid in the United States, there is no comprehensive European overview of the state of knowledge about evolution and acceptance of evolution as well as their relationship to date (reasons for that are discussed in Chapter 2.6.1).

2.4 Measuring instruments

Many instruments that seek to measure acceptance of evolution or knowledge about evolution have been developed. Additionally, in some studies (e.g., Deniz & Sahin, 2016; Irez & Bakanay, 2011; Lammert, 2012; Mead et al., 2018; Stanisavljević et al., 2013; Tekkaya et al., 2012), the initial instruments have been modified, such as the number or even content of items. In the following, only the initial instruments and their sources of evidence for validity and reliability are discussed because of the large number and varying quality of the modified instruments (AERA et al., 2014). The focus will be on commonly used instruments, according to recent reviews in the literature (Beniermann, 2019; Mead et al., 2019).

2.4.1 Instruments measuring knowledge about evolution

Assessing Contextual Reasoning about Natural Selection (ACORNS; Nehm et al., 2012). The ACORNS consists of open-ended questions based on the ECT (Bishop &

Anderson, 1990). The questions contain the key concepts *natural selection* and *non-adaptive change*. Nehm et al. (2012) developed the ACORNS to assess "[…] students' abilities to use natural selection to explain evolutionary change […]" (Nehm et al., 2012, p. 93) in different reasoning contexts like *trait gain vs. loss*, *animals vs. plants*, or *familiar vs. unfamiliar taxa/traits*.
It was tested with 28 undergraduate students. Nehm et al. (2012) assumed content validity because numerous biological scenarios are represented by the questions. The authors conducted student interviews for internal consistency and provided evidence for an appropriate external structure by comparing the ACORNS results with the results of another commonly used evolution knowledge instruments (CINS, see later in this Chapter). Reliability was tested in two ways. Good internal consistency was proved via Cronbach's alpha and IRR (Nehm et al., 2012).

Conceptual Assessment of Natural Selection (CANS; Kalinowski et al., 2016). The CANS contains 24 multiple-choice questions on *natural selection*. Kalinowski et al. (2016) focused on four species because these examples are supposed to expose particular misconceptions: anteaters (*use and disuse*), bowhead whales (*effect of the environment on evolution*), saguaro cacti (*thinking about plants*), and mosquitoes (*thinking about resistance to disease or pesticides*). The 24 multiple choice questions aim to assess five concepts that relate to natural selection: *variation, selection, inheritance, mutation,* and *evolution by natural selection.* Three to five answer options are provided. All questions use common alternative conceptions as distractors (Kalinowski et al., 2016).
The CANS aims to assess the knowledge of college students in introductory biology courses. It was tested with 218 students enrolled in an introductory biology course designed for biology majors. Kalinowski et al. (2016) provided two sources of evidence for each reliability and validity. The reliability of the instrument was proved based on internal consistency via Cronbach's alpha and stability via test-retest administration. Content validity was examined by an expert review, intention of answer processes (substantive) by student interviews (Kalinowski et al., 2016).

Conceptual Inventory of Natural Selection (CINS; Anderson et al., 2002). The CINS consists of 20 multiple choice questions on *natural selection*. The framing of each question is a real-world context based on scientifically studied evolutionary events. The questions deal with ten different evolutionary concepts (two questions each): *Biotic* *potential, population stability, natural resources, limited survival, variation within a population, variation inheritable, differential survival, change in a population, the origin of species, and origin of variation.* Each question offers four answer options, including common alternative conceptions as distractors (Anderson et al., 2002).

The CINS aims to trigger students' basic concepts of ecology and genetics, with which they explain natural selection, rather than testing natural selection as a process itself (Anderson et al., 2002). CINS was developed to evaluate the knowledge of undergraduate non-majors (pre- and post-instruction knowledge) and undergraduate majors (pre-instruction knowledge). The final version of CINS was tested with 206 students at a community college. Anderson et al. (2002) provided one source of evidence for reliability and three sources of evidence for validity. The reliability of the instrument was measured by checking internal consistency via Kuder-Richardson 20. The content validity was examined by experts, the internal structure by a principal component analysis (PCA). PCA revealed an extraction of seven components as the best solution (with a loading > 0.4 on at least one component). The components accounted for 53 % of the total variance (Anderson et al., 2002). Since the inventory was developed by means of a heterogeneous population, the authors stated that their instrument could be generalized (Anderson et al., 2002).

Evolution Concept Test (ECT; Bishop & Anderson, 1990). The ECT contains six items on *natural selection*, two of them in an open-ended question format, and four as a 5-point rating scale supplemented by an additional handwritten explanation. Bishop & Anderson (1990) focused on three zoological examples: the evolution of the ability to run fast in cheetahs, the evolution of blind salamanders from sighted ancestors, and the evolution of webbed feet in ducks. In the cheetah and salamander item (open-ended), students should describe how a biologist would explain the respective evolutionary process. In the four rating items, students should rate different aspects of the evolution of webbed feet in ducks.

The ECT was tested with 110 non-major undergraduate students enrolled in a non-major's introductory biology course. Bishop & Anderson (1990) provided two sources of evidence for validity. Content validity was ensured by analyzing the lecture material and required texts used in the students' courses and substantive by student interviews (Bishop & Anderson, 1990). The authors indicated that reliability was checked by using interrater reliability (IRR) but did not provide any proving statistics.

Evolutionary Development Concept Inventory (EvoDevoCI; Perez et al., 2013)
The EvoDevoCI consists of eleven multiple-choice items with four answer options each. Perez et al. (2013) included six key concepts about evolutionary developmental biology. The EvoDevoCI includes zoological and botanical contexts, familiar and unfamiliar taxa, examples within and between species as well as scenarios with gain vs. loss of traits. The final version of the EvoDevoCI was tested with 539 students.
Perez et al. (2013) provided three sources of evidence for reliability and validity each. The instrument's reliability was tested based on internal consistency via Cronbach's alpha and stability via test-retest administration. Cronbach's alpha varied among the subgroups with questionable to acceptable values. Content validity was examined by expert reviews, substantive by student interviews, and external structure by using point biserial correlation (Perez et al., 2013).

Genetic Drift Inventory (GeDI; Price et al., 2014). The GeDI contains 22 agree/disagree statements on the genetic drift as a process of evolutionary change. The statements relate to six different misconceptions about genetic drift, which were identified via analyzing previous studies and interviewing students (Price et al., 2014). The authors developed the GeDI to assess concepts of upper-division biology students. GeDI's final version was tested with 661 students in upper-division biology courses at three institutions (Price et al., 2014). The authors provided two sources of evidence for reliability and three sources of evidence for validity. The reliability of the instrument was tested based on internal consistency via Cronbach's alpha and stability via test-retest administration. Cronbach's alpha varied over the different courses between questionable and good values. Content validity was examined by an expert review and literature analysis, substantive by student interviews, and generalization by surveying different populations (Price et al., 2014).

Knowledge About Evolution (KAEVO; Beniermann, 2019). The KAEVO consists of three parts (A, B, and C) including 14 multiple-choice questions, 18 true/false statements, as well as three timeline estimation items. The items were developed based on multiple other knowledge about evolution tests (e.g., Bishop & Anderson, 1986; Brennecke, 2015; Graf, 2008; Jiménez-Aleixandre, 1992; Lammert, 2012). KAEVO-A contains nine multiple choice questions about the evolutionary key concepts *evolutionary adaptation and natural selection, biological fitness, speciation,* and *heredity of phenotype changes*.

Multiple contexts (zoological and botanical as well as familiar and unfamiliar contexts) were used for the questions on *evolutionary adaptation and natural selection*. KAEVO-B contains six true/false statements about different evolutionary concepts like *speciation* or *human evolution*. KAEVO-C comprises three items on *deep time*. Respondents should classify three events in the history of the Earth, the existence of humans, dinosaurs, and the first living beings, chronologically on a timeline without any dates that ranges from 'origin of the Earth' to 'today.'

The KAEVO was tested with four different cohorts of respondents (*N* = 1,129): high school students (Grades 7, 9, 10, and 11), biology university students, and biology teachers (Beniermann, 2019). The intended target group for the KAEVO is high school students (from Grade 7 on), undergraduates (majors and non-majors), and teachers (Beniermann, 2019). Beniermann (2019) provided five sources of evidence for validity and one source of evidence for reliability. Content validity was tested in multiple ways. First, by a literature review of instruments to assess understanding of evolution or single evolutionary concepts. Second, by two interview surveys on undergraduates and high school students for developing the distractors. Third, by expert ratings (experts in the field of biology education and evolutionary biology) of the test items. Fourth, substantive validity was supported by a pre-test with younger learners (Grades 7-12). The internal structure was tested by a Principal Component Analysis, the external structure with correlational analyses. Fifth, a comparison across contextual diversity by testing four different age groups lead to the assumption that the scores are meaningful across populations and contexts. In terms of reliability, the internal consistency was tested by Cronbach's alpha (Beniermann, 2019).

Measure of Understanding of Macroevolution (MUM; Nadelson & Southerland, 2009). The MUM contains 27 multiple-choice items with four answer options each, and one open-ended question. Nadelson & Southerland (2009) included five different key concepts for the understanding of macroevolution: *deep time, phylogenetics, speciation, fossils,* and *nature of science*.

The MUM was tested with three cohorts of students: 667 students enrolled in a first-semester introductory biology course and two additional cohorts of students (*n* = 74 and *n* = 54) of an upper-level evolution course (Nadelson & Southerland, 2009). Nadelson & Southerland (2009) provided one source of evidence for reliability and validity each. Content validity was supported by textbooks analysis and an expert review. The authors tested internal consistency of the MUM for the entire sample and all three single cohorts via Cronbach's alpha reporting good values for the entire sample and questionable to good values for the subgroups.

2.4.2. Instruments measuring acceptance of evolution

Attitudes Towards Evolution (ATEVO; Beniermann, 2019). The ATEVO consists of eight five-point rating scale items. Each item consists of a statement and the five answer options 'agree', 'somewhat agree', 'undecided', 'somewhat disagree', and 'disagree.' The instrument was developed to measure only acceptance of evolution, meaning that it should not contain any religious statements and should only require very basic knowledge about evolution (Beniermann, 2019). For the ATEVO, the term 'attitude' was defined as it describes a connection between a word, fact, individual object (attitude object), and its subjective evaluation. Thus, 'attitude towards evolution' describes personal opinions about the statement that evolution occurs as positive, neutral, or negative. A positive attitude towards evolution is called 'acceptance,' while a negative attitude is called 'rejection.' Beniermann (2019) stated that the ATEVO can be separated into two subscales with four items each. ATEVO-EG measures attitudes towards evolution in general, ATEVO-EM attitudes towards evolution of the human mind.

The ATEVO was tested in four studies (*N* = 9,311) on the general public, high school students, biology and non-biology undergraduates, biology teachers, and a group of non-religious people to ensure that it is usable for the general public, groups of different ages and education, as well as non-religious and religious people (Beniermann, 2019).

Sources of evidence for validity and reliability are the same as for the KAEVO (see Chapter 2.4.1), as they were developed together, except for the ATEVO being tested in four instead of one study.

Evolutionary Attitudes and Literacy Survey (EALS; Hawley et al., 2011; EALS short form; Short & Hawley, 2012). Two forms of the EALS were developed, the long form (EALS) including 104 rating-scaled questions, and the short form (EALS-SF) containing 64 rating-scaled items. The EALS consists of 16 lower- and six higher-order constructs that assess factors, which could potentially influence the acceptance of evolution, such as moral values, attitudes towards Creationism or Intelligent Design, and science understanding and attitudes.

The EALS was tested with 371 undergraduates representing nearly 40 different majors (Hawley et al., 2011). The authors provided one source of evidence for reliability and validity each. Evidence for internal structure validity was provided with loadings from a confirmatory factor analysis (CFA). The reliability of the instrument was tested based on internal consistency via Cronbach's alpha (Hawley et al., 2011).

The EALS-SF was developed because the authors assumed the EALS-LF to be too excessive for educators and researchers (Short & Hawley, 2012). The instrument was tested with 526 undergraduates from an introductory biology course. Evidence for validity and reliability was provided using the same methods as for EALS (Short & Hawley, 2012).

Generalized Acceptance of Evolution Evaluation (GAENE; Smith et al., 2016). The GAENE contains 13 rating-scaled items explicitly developed to measure only acceptance of evolution without measuring religiosity and knowledge about evolution simultaneously (Smith et al., 2016). The authors define acceptance of evolution as "[…] the mental act or policy of deeming, positing, or postulating that the current theory of evolution is the best current available scientific explanation of the origin of new species from preexisting species." (Smith et al., 2016, p. 1296).

The GAENE was tested with high school students as well as undergraduates of multiple institutions. The authors provided evidence for validity by Rasch analysis and a principal component analysis (PCA). Reliability was tested via Cronbach's alpha (Smith et al., 2016).

In response to concerns with prior validation (Sbeglia & Nehm, 2018), the GAENE was revised (Glaze et al., 2020). New items were added to address extremes, problematical items were removed from the instrument. Subsequently, the new version of the GAENE was validated via convergent validity and Rasch analysis.

Inventory of Student Acceptance of Evolution (I-SEA; Nadelson & Southerland, 2012). The I-SEA contains 24 items on three different topics: *microevolution, macroevolution,* and *human evolution*. It was tested with high school students as well as undergraduates.

The authors provided two sources of evidence for validity and one source of evidence for reliability. Content validity was supported by expert reviews. An exploratory factor analysis (EFA) was used to provide evidence of internal structure. Internal consistency was provided with Cronbach's alpha (Nadelson & Southerland, 2012).

Measure of Acceptance of the Theory of Evolution (MATE; Rutledge & Warden, 1999; Rutledge & Sadler, 2007; Barnes et al., 2022). The MATE consists of 20 five-point rating scale items and was developed to measure the acceptance of evolution by assessing perceptions of concepts considered fundamental to evolution. The original version (Rutledge & Warden, 1999) was tested with high school biology teachers. However, the MATE was updated twice. The first updated version was tested with undergraduate non-majors (Rutledge & Sadler, 2007). The second updated version, the 'MATE 2.0', was revised based on cognitive interviews with 62 students and subsequently tested with 2881 students in 22 classes.

The authors reported evidence for content validity by an expert review, internal structure validity by a PCA, and evidence for internal consistency reliability using Cronbach's alpha (Rutledge & Warden, 1999). For the first updated version, only evidence for reliability using Cronbach's alpha was reported (Rutledge & Sadler, 2007). The MATE 2.0 was validated by cognitive interviews, a Rasch dimensionality analysis, and a correlation analysis with other measures of acceptance of evolution (Barnes et al., 2022).

2.5 Measuring issues

The quality of measuring instruments influences the results and finally the conclusions drawn in research (Mead et al., 2019). However, numerous international comparative surveys measuring the knowledge about evolution (European Commission, 2005) or the acceptance of evolution (Brenan, 2019; Hameed, 2008; Ipsos Global @dvisory, 2011; Miller et al., 2006; Pew Research Center, 2015) only used one multiple choice question with few answer options to make assertions about the respondents' level of knowledge or acceptance. A limited number of answer options (true/false, e.g., in Miller et al., 2006) forces respondents to choose between few options on a complex topic (Pobiner, 2016). These study results can therefore be misleading. Another crucial point is that it is questionable to declare a question in a knowledge about science test (e.g., in European Commission, 2005) as a question about acceptance of evolution (see Miller et al., 2006), as lacking knowledge can then be misinterpreted as a creationist position.

It is essential to distinguish strictly between knowledge about evolution and acceptance of evolution in measuring instruments. Although some people may have scientifically accurate conceptions about evolution, they still can reject that evolution is actually happening (McCain & Kampourakis, 2018). Another potential bias is caused by several comparative studies focusing merely on human evolution to measure acceptance of evolution (e.g., Brenan, 2019; Pew Research Center, 2015). Human evolution causes higher discomfort (Rughiniş, 2011) and is known to be less accepted (Barnes et al., 2019; Beniermann, 2019) than the evolution of plants and animals.

Mead et al. (2019) emphasized the importance of high measurement standards in their review of the most commonly used measuring instruments in evolution education research. They found that some instruments entirely lacked evidence for reliability and validity (e.g., KEE (Moore & Cotner, 2009)) and several original populations had a narrow character (e.g., MATE). Additionally, Mead et al. (2019) stated that only scarce new evidence of validity or reliability was provided for new uses of the instruments and some authors did not provide information about the version or the portion of the original instrument that was used (e.g., Gregory & Ellis, 2009). Summed up, it can be stated that it is crucial to verify the quality of an instrument again if it has been changed in any way or is intended to be applied to a new target group. Conclusions drawn from studies, in which these measurement standards were violated, must be taken with caution.

2.5.1 Definition of key constructs

In previous studies, inconsistent definitions of terms like *knowledge, attitudes,* and *acceptance* lead to different operationalizations (Ha et al., 2012; McCain & Kampourakis, 2018; Smith et al., 2016). A prominent example is the MATE, one of the most commonly used evolution acceptance instruments. It is not clear what is meant by *acceptance* in the context of the MATE, because it is not clearly defined (Smith 2010; issues on existing evolution acceptance instruments, for instance, the MATE, are discussed in Chapter 2.5.3.

It is discussed in the literature if this ambiguous use of key constructs could be mainly responsible for the partially conflicting results in science education research (Konnemann, Asshoff, & Hammann, 2012; Mead et al., 2019; Smith et al., 2016).

2.5.2 Complexity of knowledge about evolution

As discussed in Chapter 2.1, the topic *evolution* consists of several underlying key concepts. Regarding the gain of knowledge, these concepts are independent of each other (see e.g., Beniermann, 2019). In particular, this means that a student could potentially understand natural selection while not understanding speciation at all. Thus, when measuring knowledge about evolution, it is important to check what key concepts are covered by the measuring instrument. It can be assumed that an instrument that solely asks for natural selection can only measure knowledge about natural selection and not knowledge about evolution.

Most of the instruments that are intended to measure knowledge about evolution (see Chapter 2.4.1) focus solely on natural selection (the CANS, Kalinowski et al., 2016; the CINS, Anderson et al., 2002; the ECT, Bishop & Anderson, 1990) as one of the main mechanisms of evolution. Other instruments cover the concepts *evolutionary developmental biology* (the EvoDevoCI, Perez et al., 2013), *genetic drift* (the GeDI, Price et al., 2014), or *macroevolution* (the MUM, Nadelson & Southerland, 2009). The KAEVO (Beniermann, 2019), however, is so far the only instrument that was developed to measure the knowledge about numerous evolutionary concepts, including both microevolution and macroevolution. It is crucial to choose the best fitting instrument for the intended purpose when planning a survey, for instance, the MUM if only the knowledge about macroevolution should be surveyed. However, it should be stated that data gathered with different instruments should not be compared in the sense of higher knowledge in group A than in group B, since the comparison is then biased because different evolutionary concepts are covered.

2.5.3 Measuring issues in evolution acceptance instruments

Within the last years it has been repeatedly shown that different evolution acceptance instruments can lead to different results in comparable target groups (Barnes et al., 2019; Konnemann, Asshoff, & Hammann, 2016; Metzger et al., 2018; Rachmatullah et al., 2018; Romine et al., 2018; Sbeglia & Nehm, 2018; Sbeglia & Nehm, 2019). There are several explanatory approaches for this problem. First, similar to the issue discussed in Chapter 2.5.2, the evolution acceptance instruments' varying foci on human evolution, microevolution, macroevolution, or evolution in general may explain the inconsistent results (Barnes et al., 2019). Studies in the United States showed that the acceptance of microevolution is higher than the acceptance of macroevolution or human evolution (Barnes et al., 2019; Nadelson & Hardy, 2015; Nadelson & Southerland, 2012). Second, the varying and partially unclear definition of the term *acceptance* may be a reason for the diverging results (see Chapter 2.5.1). Third, items may unintentionally measure for instance knowledge about evolution or religious faith instead of acceptance of evolution (Beniermann, 2019; Konnemann et al., 2012). The MATE (see Chapter 2.4.2 for instrument's details) contains items asking for the age of the Earth, which may mask not knowing the age of the Earth as a Creationist position (Beniermann, 2019).

Summed up, it can be stated that multiple obstacles regarding measurement standards have to be cleared when assessing knowledge about evolution and acceptance of evolution.

2.6 Evolution education research in Europe

In contrast to the United States, the amount of conducted research varies between European countries. The situation in Europe is characterized by fragmented research communities, different languages, and different education systems, making comparisons of acceptance of evolution and knowledge about evolution between respondents of different European countries much more complicated than within the United States. For instance, instruments usually must be translated to the local language before surveying, which may bias the results. Additionally, as discussed in Chapter 2.5, study results of different countries can only be compared to each other if the same instruments have been used and numerous measurement standards have been followed.

Few comparisons between European countries exist (e.g., Clément 2015; Pinxten, Vandervieren, & Janssenwillen, 2020; Šorgo et al., 2014). These comparisons can help to understand how the different education systems, various cultural backgrounds within Europe may cause different acceptance of evolution and knowledge about evolution. European countries differ significantly regarding evolutionary concepts in school curricula, national anti-evolution movements, public acceptance of evolution, as well as students' knowledge about different evolutionary concepts (Graf, 2010; Harms & Reiss, 2019; Sá-Pinto et al., 2021), biology teacher education programs, and teachers' attitudes towards teaching evolution (Deniz & Borgerding, 2018). Still, a comprehensive overview of the level of acceptance of evolution and knowledge about evolution in Europe does not exist.

3 Aims of the dissertation and overview of the conducted research

Although acceptance of evolution and knowledge about evolution have been investigated for decades, several problems are still present and must be tackled (see Chapters 2.5 and 2.6). Still, numerous measuring issues, caused by evolution knowledge instruments measuring knowledge about only a few evolutionary concepts (see Chapter 2.5.2), or instruments mixing acceptance of evolution, knowledge about evolution, and religious faith (see Chapter 2.5.3), bias the body of research. Additionally, as described in Chapters 2.4 and 2.5, evidence for validity and reliability is often not provided, when using an adapted version of an instrument or an instrument in a new target group.

Fragmented research communities in Europe lead to a patchwork of research on acceptance of evolution and knowledge about evolution in Europe (see Chapter 2.6). To date, a state of the conducted evolution education research in Europe has not been systematically reviewed and published. Also, a comprehensive investigation of the level of acceptance of evolution and knowledge about evolution in a comparable target group, gathered with the same instrument, has not been conducted so far.

Thus, in a first step, the existing body of research in the field of evolution education in Europe should be systematically reviewed. In the next step, an instrument measuring both acceptance of evolution and knowledge about evolution separately must be composed. Here, all previously mentioned measurement issues must be considered. In the last step, this comprehensive instrument should be used to survey respondents of a comparable target group in several European countries.

This dissertation aims to expand the existing body of research on evolution education following these research foci:

(1) creating an overview of the state of evolution education research in Europe,

(2) composing a high-quality instrument measuring acceptance of evolution and knowledge about evolution, and

(3) conducting a standardized European cross-country assessment on acceptance of evolution and knowledge about evolution.

The following sections (Chapters 4-6) consist of the three published papers. Additionally, Table 1 provides an overview of the paper contents.

Table 1: Overview of the paper contents.

Paper I	
Publication	Kuschmierz, P., Meneganzin, A., Pinxten, R., Pievani, T., Cvetković, D., Mavrikaki, E., ... & Beniermann, A. (2020). Towards common ground in measuring acceptance of evolution and knowledge about evolution across Europe: a systematic review of the state of research. *Evolution: Education and Outreach, 13*(1), 1-24. https://doi.org/10.1186/s12052-020-00132-w
Key words	Acceptance of evolution, Europe, evolution education, evolutionary knowledge
Aims	1. Providing a systematic overview of the current state of research regarding evolution knowledge and acceptance of groups that are particularly relevant in the context of science education (students and teachers) across Europe 2. Analyzing the quality of used instruments in terms of evidence for validity and reliability
Design	Systematic analysis of the state of research
Contribution	• Corresponding author, literature review in English language for most instruments, key word search in English language for all key words, data compiling and analysis, manuscript conceptualization and writing
Paper II	
Publication	Kuschmierz, P., Beniermann, A., & Graf, D. (2020). Development and evaluation of the knowledge about evolution 2.0 instrument (KAEVO 2.0). *International Journal of Science Education, 42*, 2601-2629. https://doi.org/10.1080/09500693.2020.1822561
Key words	diagnostic assessment, evolutionary concepts, Evolution education, knowledge, learning, misconceptions
Aims	3. Introducing the KAEVO 2.0 instrument that measures knowledge about evolution comprehensively Providing sources of evidence for validity and reliability of KAEVO 2.0
Design	Instrument validation study
Sample	*N* = 406 • 136 biology university students • 124 non-biology university students 146 high school students
Contribution	Corresponding author, data gathering, data analysis, manuscript conceptualization and writing
Paper III	
Publication	Kuschmierz, P., Beniermann, A., Bergmann, A., Pinxten, R., Aivelo, T., Berniak-Woźny, J., … & Graf, D. (2021). European first-year university students accept evolution but lack substantial knowledge about it: a standardized European cross-country assessment. *Evolution: Education and Outreach, 14*(1), 1-22. https://doi.org/10.1186/s12052-021-00158-8

Key words	Europe, Evolution acceptance, evolution knowledge, higher education, multilevel modeling, socioscientific issues, religious faith
Aims	1. Providing the first comprehensive overview of the knowledge about evolution and the acceptance of evolution in Europe based on comparable data 2. Identifying influencing factors on acceptance of evolution 3. Identifying the impact of diverse cultural backgrounds and evolution-related curricula on acceptance of evolution in participating European countries
Design	Cross-country comparative pen-and-paper study
Sample	*N* = 11,723 • first-year university students of 26 European countries, who had recently finished upper secondary education and were enrolled in a biology-related or non-biology study program • students who are not older than 25 years • students who graduated from upper secondary education less than two years before the survey
Contribution	Corresponding author, principal investigator of the project, data gathering, data analysis, manuscript conceptualization and writing

4 Paper I

Kuschmierz, P., Meneganzin, A., Pinxten, R., Pievani, T., Cvetković, D., Mavrikaki, E., ... & Beniermann, A. (2020). Towards common ground in measuring acceptance of evolution and knowledge about evolution across Europe: a systematic review of the state of research. *Evolution: Education and Outreach, 13*(1), 1-24. https://doi.org/10.1186/s12052-020-00132-w

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Evolution: Education and Outreach

REVIEW ARTICLE

Open Access

Towards common ground in measuring acceptance of evolution and knowledge about evolution across Europe: a systematic review of the state of research

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Abstract

Background: Relatively little information is available regarding the level of acceptance of evolution and knowledge about evolution in different educational settings in Europe. The aim of the present study is to fill this gap and provide a comprehensive overview of the current state of research regarding evolutionary knowledge and acceptance of students and teachers across Europe, based on a systematic literature review.

Results: We identified 56 papers for the period 2010–2020, presenting results for 29 European countries. Both knowledge and acceptance of evolution were assessed in 17 studies. Out of 13 instruments most commonly used in the literature, five have been used in the European context so far: ACORNS, CINS, I-SEA, KEE and MATE. Thirty-one other instruments were identified of which 16 were used in studies on knowledge and 15 in studies on acceptance. The extent of knowledge was hard to compare even within groups of the same education level due to the application of different instruments and assessment of different key concepts. Our results illustrate the persistence of misconceptions through all education levels. Comparing acceptance among different education levels and countries revealed a high diversity. However, a lack of evolution in curricula tended to be associated with rejection of evolution in some countries. European studies that investigated both acceptance of evolution and knowledge about evolution varied highly concerning the existence and strength of the relationship between these factors. However, some trends are visible, such as an increase of strength of the relationship the higher the education level.

Conclusions: The present review highlights the lack of a standardized assessment of evolutionary knowledge and acceptance of evolution across Europe and, therefore, of reasonably comparable data. Moreover, the review revealed that only about one-third of all studies on acceptance and/or knowledge about evolution provided evidence for local validity and reliability. We suggest the use of assessment categories for both knowledge and acceptance instruments to allow for interpretation and comparison of sum scores among different sample groups. This, along with prospective comparative research based on similar samples, paves the way for future research aimed at overcoming current biases and inconsistencies in results.

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Keywords: ACORNS, Acceptance of evolution, CINS, Europe, Evolution education, Evolutionary knowledge, I-SEA, KAEVO, KEE, MATE

Background and aim of the paper

Evolution is the backbone of modern biological studies as it provides the unifying framework within which all biologists, from a diversity of branches and subdisciplines, ask questions about the living world. A basic understanding of central evolutionary concepts is thus considered essential for biological education and scientific literacy. The Council of Europe (COE) and different scientific organizations within Europe have underlined the importance of promoting the teaching of evolution in school curricula as a fundamental scientific theory and have opposed teaching creationism on an equal footing, as claiming scientific respectability (e.g., COE, Resolution 1580 2007; Ecsite 2008; German National Academy of Sciences Leopoldina 2017). Only in the light of evolutionary knowledge, advances in medical research and the risks involved in biodiversity decline and climate change can truly be comprehended. However, numerous studies provided evidence of the difficulties students (e.g., Fiedler et al. 2018; Göransson et al. 2020; Torkar and Šorgo 2020) and even teachers (e.g., Athanasiou et al. 2016; Tekkaya et al. 2012; Yates and Marek 2013) have in understanding evolution. In the past decades, scientists and educators have explored understanding of evolution across a variety of educational levels and publics, in order to identify possible causal explanations and barriers that make evolution so difficult to understand (Ha et al. 2012; Reiss and Harms 2019; Yates and Marek 2014). The general poor understanding has been attributed to a wide variety of cognitive, epistemological, religious and emotional factors (Alters and Nelson 2002).

Misconceptions about evolution

A fundamental problem in evolution education is that many students hold remarkably high levels of misconceptions about basic evolutionary principles like natural selection, adaptation, speciation or phylogeny (Harms and Reiss 2019a). A *misconception* is a commonly held idea that is inconsistent with scientific understanding and that is very resistant to instruction, usually developing in early childhood as part of a very intuitive but naïve understanding of the structure of the world but which persists into adulthood, being held both by novices and experts (see Gregory 2009 for a review). These include in particular anthropomorphic misconceptions (both internal, i.e., attributing intentional, adaptive change to organisms, and external, i.e., conceiving natural selection as an intentional or conscious agent; Gregory 2009), Lamarckian misconceptions (in its precise meaning: e.g., evolutionary changes can happen due to use and disuse of organs; individuals can pass acquired traits down to their offspring; Kampourakis and Zogza 2007) and "common sense" teleological ideas (e.g., evolution is goal-directed and traits evolve in order to serve specific purposes). However, as many authors have made clear, teleological thinking comprises a wide variety of forms and not all of them are scientifically unacceptable, nor provide an obstacle for evolution didactics (González Galli and Meinardi 2011; Hammann and Nehm 2020; Kampourakis et al. 2012a, b; Kampourakis 2020).

Evolution in the European school context

A major cause of these misconceptions could be that evolution—or some major aspects of it as human evolution for example—is given little importance in some European countries' school syllabi/curricula (German National Academy of Sciences Leopoldina 2017; Pinxten et al. 2020; Quessada and Clément 2011; Reiss 2018) or is presented in an inappropriate way (Sanders and Makotsa 2016). However, although such reviews rate European curricula often as insufficient and/or inappropriate in terms of evolutionary contents, huge differences between countries are visible: For example, in Turkey, which is ranking in the lowest positions regarding the acceptance of evolution (Miller et al. 2006), Evolution was reasonably taught in schools in the early years of the Republic of Turkey (Peker et al. 2010). However, in 1985 creationism was included in the biology curriculum, overshadowing the teaching of evolution (Peker et al. 2010) until finally, in 2017, evolution was removed from high school textbooks (Genç 2018). In Greece, which is another low ranking country regarding acceptance of evolution (Miller et al. 2006), *"the public educational system is very successful in totally exiling evolution education from all its 'territory' without any profound prosecution or any other similar action, for many years"* (Athanasiou and Papadopoulou 2015, p. 844). It is done by positioning the chapter on evolution last in biology textbooks (therefore teachers usually lack time to teach it (Prinou et al. 2005)) or by omitting it from the high school curriculum and the university entrance exams (a situation that tends to change in recent years). Until recently, in Flanders, the Dutch speaking region of Belgium, the teaching of evolution was also largely restricted to the last weeks of the final year of general secondary education, as a separate and last chapter in the textbooks (De Schutter et al. 2005; D'Haeninck et al. 2009). In contrast, in the Netherlands, where public acceptance of evolution is rather high according to Miller et al. (2006), evolution and natural selection are already explicitly addressed in the fourth year of general secondary education and in a more integrated manner throughout the biology curriculum of upper secondary education (Geraedt and Boersma 2006; Smith and Siegel 2004). Likewise, in France, where public acceptance of evolution is high (Miller et al. 2006), evolution is present and central in the science syllabi through all school years *"starting by an initiation at the Primary School, a development in Lower Secondary School and a large deepening in the scientific section of High Schools"* (Quessada and Clément 2018, p. 213). In England, where public acceptance of evolution is also high (Miller et al. 2006), evolution is embedded in the secondary school curricula but also a contested topic (Reiss 2018). Students in Scotland are taught about evolution from the third year of secondary education on (Downie et al. 2018). The Scottish general science curriculum covers the topics biodiversity and interdependence of living organisms before dealing with natural selection (Downie et al. 2018). In Germany (high acceptance of evolution; Miller et al. 2006), Switzerland (moderate ranking country regarding acceptance of evolution; Miller et al. 2006), Austria (rather low ranking compared to other European countries regarding acceptance of evolution; Miller et al. 2006), and Luxembourg (rather high acceptance of evolution; Miller et al. 2006), primary education does not address evolution (Eder et al. 2018). The situation at the secondary level is complex due to many different curricula in the German federal states and the cantons of Switzerland and different school types for lower and higher secondary education. However, Evolution is taught in all four countries once in lower and upper secondary education each. Therefore, Eder et al. (2018) stated that students who leave school in those four countries after higher secondary education should have at least basic knowledge about evolution.

Curricula and textbook analyses are hard to accomplish but could reveal gaps in evolution education. A comprehensive analysis and assessment of European curricula based on a standardized framework (Understanding Evolution. 2020) is currently in preparation (EuroScitizen COST Action (CA17127)[1]). The "BIOHEAD-Citizen project" (Biology, health and environmental education for better citizenship) was one of the first attempts to analyze countries' curricula and included 13 European and six non-European countries (Carvalho et al. 2007). Although they did not search for the coverage of evolution but only for "human evolution" in school curricula and textbooks, they provided some very useful results such as that *"the social context strongly influences the way evolution is (or is not) taught, particularly human evolution"* (Carvalho et al. 2007, p. 305).

[1] www.euroscitizen.eu.

Evolution education research in Europe

To date, the majority of evolution education research has been carried out in the USA, which may be mainly explained by the particular public resistance to evolution, as the regular publication polls demonstrate (Brenan 2019). However, empirical evidence shows that population polls (e.g., Brenan 2019) more likely measure differences in religious faith than in acceptance of evolution (Beniermann 2019; McCain and Kampourakis 2018).

The situation in Europe is much more diverse, as the more fragmented education research communities, different educational systems and languages make it challenging to gather comparable data for different European countries. Comparable data sets of European countries are very rare (but see e.g., Clément 2015a; Pinxten et al. 2020; Šorgo et al. 2014). Furthermore, a diverse science education research community may more often use national measuring instruments. In contrast to the USA, instruments usually have to be translated in order to conduct cross-country comparisons in Europe, which is a possible source of data bias. On the other hand, European countries differ significantly concerning public acceptance of evolution, national anti-evolution movements, evolutionary concepts in school curricula and biology teacher education programs, teachers' attitudes towards teaching evolution (Deniz and Borgerding 2018), teachers' acceptance of evolution (Clément 2015a) as well as the available study results about students' knowledge about different evolutionary concepts (Harms and Reiss 2019b). As a result, the various cultural backgrounds as well as different school systems within Europe can serve as a foundation for interesting research questions and hypotheses.

Relationships between knowledge, acceptance and religious faith

At present, relatively little information is available with respect to the level of acceptance and understanding in Europe, where religious beliefs generally are assumed to interfere less with attitudes towards evolution (Miller et al. 2006). But even in European samples, the relationship between attitudes towards evolution and religious faith was shown to be generally negative and mostly strong (e.g., Beniermann 2019; Graf and Soran 2010). However, religious diversity increased within the last decades, especially in Europe (differentiation within religions, migration, raising interest in alternative new age spirituality; Pollack et al. 2012; Stolz et al. 2014).

The relationship between attitudes towards evolution and knowledge about evolution, in particular, is another central issue for science education research (Dunk et al. 2019). To date there is no clear consensus in the evolution education community about the nature and the extent of this relationship (e.g., Barnes et al. 2019; Dunk et al. 2019; Glaze and Goldston 2015). The application of different measuring instruments (e.g., Barnes et al. 2019; Mead et al. 2019; Smith et al. 2016) as well as the different use of terms concerning the key constructs (Konnemann et al. 2012; Smith and Siegel 2016) may be the main reasons for inconsistent results in this research area. This is a crucial issue for science education, since studies on attitudes and knowledge about evolution as well as their relationship lead to conclusions regarding the teaching of evolution (e.g., for Turkey Annaç and Bahçekapili 2012).

Measuring issues

However, to be able to investigate this relationship and to compare surveys with diverging results, the utilized measuring instruments should measure equivalent constructs. Besides this aspect of content validity, comparative investigations require appropriate evidence for validation in the local context of the single studies (AERA 2014). Since Nehm and Schonfeld (2008) raised the issue of measuring knowledge about natural selection and the subsequent debate (Anderson et al. 2010; Nehm and Schonfeld 2010), the discourse concerning measurement issues in evolution education accelerated and has been addressed continuously within the last years (e.g., Anderson et al. 2010; Barnes et al. 2019; Beniermann 2019; McCain and Kampourakis 2018; Mead et al. 2019; Novick and Catley 2012; Smith et al. 2016). In the introduction to a special issue devoted to the topic of evolution assessment, Nehm and Mead (2019) have recently underlined the importance of drawing greater attention to research on the measurement and assessment of knowledge, attitudes and skills that are central to evolution education, thus calling for further research efforts in this area. In fact, multiple challenges arise in this context.

First, the partly missing definitions of key constructs like *attitudes*, *acceptance*, *knowledge* and *understanding* lead to different operationalizations (Ha et al. 2012; Konnemann et al. 2012; McCain and Kampourakis 2018). In the following, we will use the term *knowledge* instead of the often-used term *understanding* when referring to measuring instruments that focus on content knowledge. This is in accordance with Smith and Siegel (2016), who pointed out that a *"student gains knowledge (*via *instruction, self-study,* etc.*) upon which she can build understanding"* (Smith and Siegel 2016, p. 486). The term *acceptance*, hereafter, describes a positive *attitude* towards evolution, while a negative attitude is called *rejection*. Second, Barnes et al. (2019) showed how different evolution acceptance instruments can sometimes lead to diverging results regarding the level of acceptance when applied to the same population. This indicates a potential bias in research results and the related conclusions in evolution education studies using different instruments to assess acceptance of evolution. Third, it was shown that acceptance is higher for microevolution than for human evolution (Barnes et al. 2019) as well as for evolution in general than evolution of the human mind (Beniermann 2019). Hence, the differences between these have to be considered when measuring evolution acceptance (Rughinis 2011; Kampourakis and Strasser 2015). Fourth, knowledge about evolution may be seen as a multidimensional construct and therefore results depend on the evolutionary concept that is assessed (Kuschmierz et al. 2020). In addition, given the unique and complex nature of context in evolutionary thinking and reasoning, evolution assessment tasks intended to measure knowledge and/or alternative conceptions may be characterized by heightened sensitivity to context effects. Nehm and Ha (2011) indeed showed that the specific scenarios/contexts in which students are asked to reason, evoke different types, magnitudes, and arrangements of key concepts of natural selection and alternative conceptions. However, the vast majority of evolution education studies have failed to carefully consider or control for context effects of items in assessment tasks (Son and Goldstone 2009, but see Nehm et al. 2012). Fifth, Mead et al. (2019) pointed out the importance of measurement standards for instruments measuring evolutionary knowledge and acceptance. They reviewed 13 different evolution education assessment instruments with respect to the evidence supporting their validity and reliability. Mead et al. (2019) revealed validity and reliability issues for some often-used instruments. Additionally, most instruments were validated for only one specific population. These findings indicate that it is difficult to compare the results gathered with different instruments. Another crucial point is that many studies only used parts of published instruments or modified versions, which may affect how well an instrument measures the intended construct (Mead et al. 2019).

Group comparisons such as between students of different grades, people from different countries or regarding the effect of different instructions are only reasonable, if comparable data is available for all groups. It is therefore important to use instruments for which there is supporting evidence to measure the same construct or ideally even the same instrument and similar target groups. Much research has been conducted in the USA with numerous instruments and target groups (Dunk et al. 2019). However, even on this database, questions about the relationship between acceptance and knowledge remain.

Objective

In recently published papers, authors emphasize the crucial importance of ongoing work to investigate the relationship between evolution acceptance and knowledge (e.g., Barnes et al. 2019; Dunk et al. 2019; Mead et al. 2019), since the assessment of these variables is a crucial issue for science education research (Dunk et al. 2019). The aim of the present article is to contribute to this ongoing challenge by providing an overview of the current state of research regarding evolutionary knowledge and attitudes of students and teachers across Europe, as these groups are of particular relevance in the context of science education. In contrast to the existing global overviews (e.g., Deniz and Borgerding 2018; Harms and Reiss 2019b), the present work aims at filling the gap in the European context, that has not been covered by any overview so far. Thus, we focus exclusively on European studies and the comparability of their research findings based on an analysis of the used measuring instruments, surveyed target groups within the field of education and provided evidence for local validity and reliability. The study results on evolutionary acceptance and/or knowledge about evolution conducted in European countries as well as the instruments used and evidence for local validity and reliability are presented on the basis of a systematic literature review. Comparisons across different European countries, target groups and instruments are evaluated. However, having the methodological shortcomings in mind, validity issues are subsequently discussed based on the literature review on evidence for local validity.

Methods

Process of literature review

To investigate how frequently commonly used instruments for measuring evolutionary knowledge and acceptance are applied across Europe, a citation search in Google Scholar was performed from February to March 2020. The citation search was conducted for all 13 instruments identified by Mead et al. (2019) as the most commonly used (see Additional file 1). Starting with the original publications of the instruments, all papers that were listed as "cited by" and written in English or in one of the authors' spoken languages (Croatian, Dutch, German, Greek, Italian, Macedonian, Serbian, and Slovenian) have been reviewed. Focusing on the current state of research, only results of the period 2010–2020 have been examined.

The surveyed European sample, the used research instrument, all relevant results regarding knowledge and acceptance of evolution as well as the correlation between these variables and correlations between acceptance and religiosity as a possible predictor were extracted. Additionally, we reported sources of evidence for validity and reliability that were provided in the identified papers. In doing so, we focused on the presentation of established measures of reliability (e.g., Cronbach's α) and internal structure as a measure of validity (e.g., Principal Component Analysis [PCA]) as well as other sources of reliability or validity in cases where the respective authors directly refer to the concepts of reliability and/or validity (e.g., expert review for content validity). We also took under consideration if the original instrument, a modified version or even only single questions were used and whether the original instrument was translated before implementation or not. In the case of pre-post intervention studies, we only took pre-test results into account. We did not include studies that focused on qualitative research (e.g., interviews). Moreover, we only included studies in which evolutionary knowledge and/or acceptance were not only control or predictor variables without results being presented in detail (e.g., mean score). A total of $N=27$ papers was identified using five of the 13 commonly used instruments (ACORNS, CINS, I-SEA, KEE, MATE, see Additional file 1).

To additionally cover all results concerning knowledge and acceptance of evolution by students and teachers in Europe gathered with other instruments, we performed a supplementary keyword search in Google Scholar, similar to the keyword search Mead et al. (2019) conducted, in April and May 2020. This search was conducted with the key words "student understanding of evolution", "student knowledge of evolution", and "student acceptance of evolution", as well as "teacher understanding of evolution", "teacher knowledge of evolution", and "teacher acceptance of evolution" in Croatian, Dutch, English, German, Greek, Italian, Macedonian, Serbian, and Slovenian. A total of $N=26$ additional papers, using 31 measuring instruments to assess attitudes and knowledge about evolution, different from those discussed in Mead et al. (2019), were identified. Three of these 31 other instruments were also used in multiple papers: The "Evolution Content Knowledge Test" (ECKT; Johnson 1985; modified by Rutledge and Warden 2000), the "Open Response Instrument" (ORI; Nehm and Reilly 2007and the "Knowledge About Evolution" instrument (KAEVO; Beniermann 2019; Kuschmierz et al. 2020). They were therefore added to the list of widespread instruments (see Additional file 1).

Score categories

The use of categories referring to levels of knowledge about evolution or acceptance of evolution allows to interpret and—if applicable—compare sum scores of

Table 1 Assessment categories for sum score categories of the evolutionary knowledge instruments

	CINS	ECKT	KAEVO 1.0	KAEVO 2.0	KEE
High knowledge	18–20	19–21	9	12	10
Rather high knowledge	15–17	16–18	8	10–11	8–9
Moderate knowledge	12–14	13–15	6–7	8–9	6–7
Low knowledge	9–11	10–12	4–5	6–7	4–5
Very low knowledge	0–8	0–9	0–3	0–5	0–3

Categories for the KAEVO 2.0 are based on the categories of Kuschmierz et al. (2020). Suggestions for all instruments based on the categories suggested for the KAEVO 2.0 (Kuschmierz et al. 2020) and the MATE (Rutledge and Sadler 2007)

Table 2 Assessment categories for sum scores of the evolution acceptance instruments

	I-SEA*	MATE (Rutledge and Sadler 2007)
Very high acceptance	106–120	89–100
High acceptance	91–105	77–88
Moderate acceptance	76–90	65–76
Low acceptance	61–75	53–64
Very low acceptance	24–60	20–52

Suggestions for I-SEA based on the categories suggested for the MATE (Rutledge and Sadler 2007)

similar sample groups gathered with different instruments (e.g., in different countries). Rutledge and Sadler (2007) defined categories of levels of acceptance for the MATE, making it easier to compare different data sets. Kuschmierz et al. (2020) also defined categories for the KAEVO 2.0. Since no categorization for the other widespread instruments was found, we recommend categories for these instruments that were used in Europe since 2010. Based on the MATE and KAEVO categories, we calculated five categories for each instrument (see Tables 1 and 2). We do not suggest categories for the ATEEK, CANS, ECT, EvoDevoCI, GeDI, MUM, EALS, and GAENE, as these instruments were not used in Europe so far.

With respect to the evolutionary knowledge instruments, these newly created categories for the CINS are in accordance with the suggestion of Anderson et al. (2010) that *"[...] anyone who scores 16/20 or higher on CINS understands natural selection quite well"*, since 16 in our scale is the mid score of the category "rather high". Additionally, these categories are in line with the suggestions of several authors who used the CINS in European countries (e.g., Annaç and Bahçekapili 2012; Buchan 2019; see Additional file 2).

For the ECKT, Rutledge and Warden (2000) reported a moderate level of knowledge about evolution, corresponding to a mean of 14.89. This is in line with our newly created categories (Table 1). Moreover, the newly created categories are consistent with suggestions of the authors who used the ECKT in Europe (e.g., Deniz and Sahin 2016; Stanisavljevic et al. 2013; see Additional file 2). Furthermore, the categories for the KAEVO 1.0 and the KEE are not in conflict with the original publications of the instruments (KAEVO: Beniermann 2019; KEE: Moore and Cotner 2009).

For the I-SEA, we did not find any suggestions for categories in the original publication, which is why we suggested categories based on the MATE. If our newly developed categories for acceptance and knowledge scores which we applied in the results section differed from the initial interpretation in the original publications (see Additional file 2 for initial interpretations), we mentioned this in a footnote.

As the ORI and the ACORNS are open-response instruments, we did not suggest assessment categories for these two instruments. However, Nehm and Reilly (2007) suggested the "Natural Selection Performance Quotient" (NSPQ) to quantify student knowledge and misconceptions.

Results on evolutionary knowledge and evolution acceptance are presented separately. Subsequently, all results on the relationship between evolutionary knowledge and acceptance are presented and compared only if a similar target group was surveyed and the same instrument was used in both studies. We did this aware of the shortcomings deriving from huge differences in terms of the provided evidence for reliability and local validity.

Education levels in Europe

Even though the type of education granting admission to the profession of teachers differs considerably between the European countries (Evagorou et al. 2015), we use the term "pre-service teachers" for all students that will become school teachers and accordingly enrolled in a teacher education program in their respective country. However, all studies focusing on pre-service teachers in the current review are referring to undergraduates.

The definition of school levels and the respective grades are also very diverse both between and even within European countries. We decided to define different school levels following the "International Standard Classification of Education (ISCED)" (European Commission 2019, see Table 3). All school levels mentioned in this paper refer to Table 3.

Results

In total, 38 papers on knowledge about evolution and 35 papers on acceptance of evolution were identified for the period 2010–2020. Seventeen of these papers dealt

Table 3 School levels based on the ISCED levels (European Commission/EACEA/Eurydice. The Structure of the European Education Systems 2019)

School levels	Early childhood education (ISCED 0)	Primary education (ISCED 1)	Secondary education	
			Lower secondary education (ISCED 2)	Upper secondary education (ISCED 3)
Grades	/	1–6	7–9	10–13
Age in years on average	0–6	6–12	12–15	15–19

Netherlands, Poland, Portugal, Romania, Russia, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, and the United Kingdom). However, the studies are unequally distributed across Europe for both knowledge about evolution (see Fig. 1) and acceptance of evolution (see Fig. 2). Many studies have been conducted in few countries, while in the majority of countries only two or less studies have been published.

Only six of these publications are cross-country comparisons (Clément 2015a; Göransson et al. 2020; Graf and Soran 2010; Kralj et al. 2018; Pinxten et al. 2020; Šorgo et al. 2014). Eight studies compared several different subgroups in the field of education (Athanasiou and Mavrikaki 2014; Beniermann 2019; Eder et al. 2011; Kampourakis et al. 2012a, 2012b; Konnemann et al. 2016; Köse 2010; Kuschmierz et al. 2020; Lazaridis et al. 2011) and 17 studies assessed both knowledge and acceptance (Akyol et al. 2010, 2012; Annaç and Bahçekapili 2012;

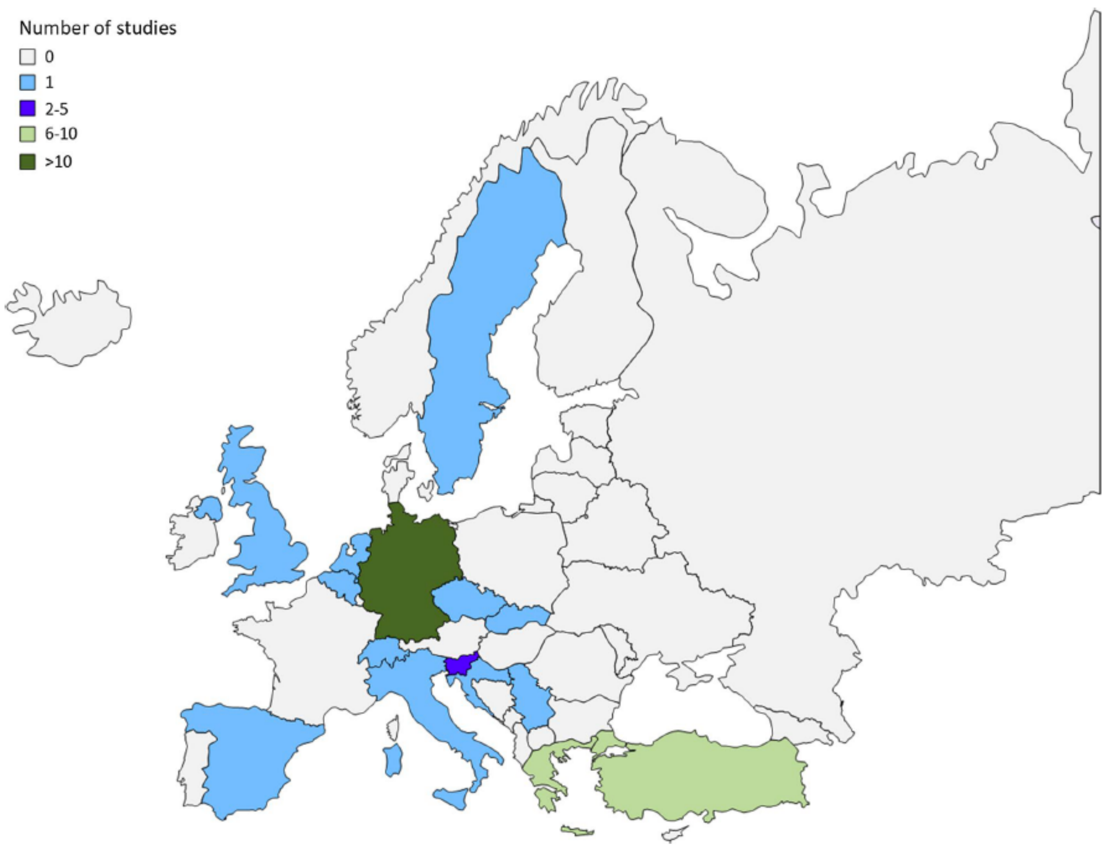

Fig. 1 Overview of the amount of studies on knowledge about evolution in Europe

with both knowledge and acceptance of evolution. The 56 identified papers include research results for 29 European countries (Austria, Belgium, Croatia, Cyprus, Czech Republic, Denmark, France, Georgia, Germany, Greece, Estonia, Finland, Hungary, Italy, Lithuania, Malta, the

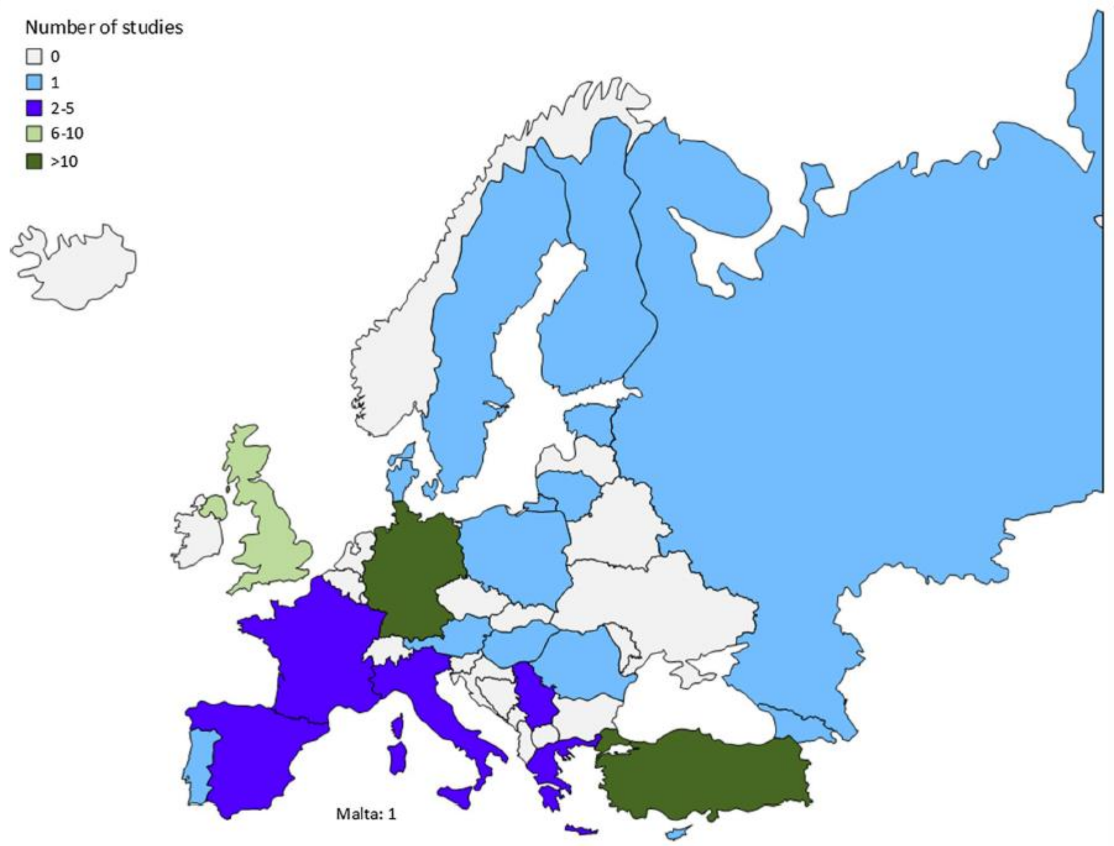

Fig. 2 Overview of the amount of studies on acceptance of evolution in Europe

Athanasiou et al. 2012, 2016; Beniermann 2019; Buchan 2019; Deniz and Sahin 2016; Fenner 2013; Gefaell et al. 2020; Graf and Soran 2010; Großschedl et al. 2018; Lammert 2012; Nehm et al. 2013; Kampourakis et al. 2012a, b; Stanisavljevic et al. 2013; Tekkaya et al. 2012). Eight of the 13 instruments, which were identified as the most commonly used instruments by Mead et al. (2019), apparently have not been used in the European context to date (see Additional file 1). We also analyzed if evidence for local validity or reliability has been provided (see Additional files 3, 4, and 5). In 14 of the 38 papers on knowledge about evolution, evidence for local validity and reliability has been provided. In two papers, only validity and in six papers only reliability was addressed. In 14 papers, no evidence for local validity and/or reliability was provided. Eleven of the 35 papers on acceptance of evolution provided evidence for local validity and reliability, four only for local validity and twelve only for reliability. In ten papers, no evidence for neither local validity nor reliability was provided. Based on this literature review, additional information, such as, for instance, used instrument(s), sample group(s) and origin(s) of the sample(s), on the identified studies is presented in Additional files 3, 4, and 5.

Knowledge about evolution

CINS

Nine surveys in six European countries (Belgium (Flanders region), Germany, Greece, the Netherlands, Turkey, the United Kingdom) used the multiple-choice instrument CINS, designed to measure the knowledge about the following 10 underlying key concepts of natural selection: origin of variation, existence of variation (in a population), variation is inherited, differential survival, limited survival, biotic potential, limited (natural) resources, change in a population, population stability and origin of species, with two items for each concept (score: 0–20; Anderson et al. 2002). Based on the results of seven of these studies, the level of knowledge among university students in Europe is very diverse, ranging from very low in Greece (biology non-majors who have not attended biology classes, $M=2.90$; Athanasiou and Mavrikaki 2014) and Turkey (psychology students, $M=5.98$; Annaç and Bahçekapili 2012), low in Greece (biology non-majors who have attended biology classes, $M=9.60$; Athanasiou and Mavrikaki 2014) and Turkey (pre-service science teachers, $M=9.91$; Tekkayaet al. 2011), moderate in Belgium (Veterinary and Biomedical Sciences university freshmen, $M_{Flemish}=12.2$, $M_{Dutch}=14.3$; Pinxten et al. 2020), Germany (primary and lower secondary education pre-service biology teachers, $M_{primary}=11.75$, $M_{lower\ secondary}=12.84$; Großschedl et al. 2018; pre-service biology teachers, $M=13.60$; Nehm et al. 2013), and Greece (first- to third-year biology majors, $M=11.6$; Athanasiou and Mavrikaki 2014), to rather high in Germany (upper secondary education pre-service biology teachers, $M=14.74$; Großschedl et al. 2018), and Greece (last year biology majors, $M=15.1$; Athanasiou and Mavrikaki 2014; $M=15.07$; Lazaridis et al. 2011).

However, on average, the cut-off score of Anderson et al. (2010) for a quite well knowledge about natural selection (a score of at least 16 based on the CINS), was only reported in Greece for biology in-service teachers ($M=16.60$[2]; Venetis and Mavrikaki 2017).

Comparisons between university student groups revealed that knowledge about evolution increased significantly with the biology education level in biology majors ($M_{1st-3rd\ year}=11.6$, $M_{postgraduate\ in\ biology\ education}=14.2$, and $M_{4th\ year}=15.1$), compared to biology non-majors with and without biology classes ($M_{no\ biology}=2.9$ and $M_{biology}=9.6$) in Greece (Athanasiou and Mavrikaki 2014), biology majors compared to early childhood education and primary education pre-service teachers ($M_{biology\ majors\ (all\ years)}=13.4$, $M_{early\ childhood}=9.7$; Lazaridis et al. 2011) and different groups of pre-service teachers in Germany ($M_{primary}=11.75$, and $M_{upper\ secondary}=14.74$; Großschedl et al. 2018). Pinxten et al. (2020) compared CINS scores between Veterinary Sciences and Biomedical Sciences university freshmen in Belgium, having completed high level biology secondary education either in Flanders, Belgium or the Netherlands and reported that Dutch students obtained a significantly higher score ($M_{Dutch}=14.4$, $M_{Flanders}=12.5$).

In two studies on in-service teachers in two European countries (Greece and the United Kingdom), a moderate level of knowledge about natural selection was reported for secondary education in-service science teachers, and a rather high level of knowledge about natural selection for the biology teachers among them, in Greece ($M_{total}=14.33$, $M_{biologists}=16.60$; Venetis 2017). In the United Kingdom, primary and lower secondary education in-service teachers also showed a moderate level of knowledge about natural selection ($M=12.84$; Buchan 2019).

A variety of misconceptions has been observed for university students in Greece (Athanasiou and Mavrikaki 2014), Flanders, Belgium (Pinxten et al. 2020), and Turkey (Tekkaya et al. 2011). Novice university students held more teleological misconceptions than advanced university students in Greece (Athanasiou and Mavrikaki 2014). Teleological misconceptions have also been found in primary and lower secondary education in-service teachers in the United Kingdom (Buchan 2019) who moreover also showed anthropomorphic and Lamarckian (soft inheritance) misconceptions. Pinxten et al. (2020) reported that the relative frequency of misconceptions elicited by the CINS was almost identical in Flemish and Dutch Veterinary and Biomedical Sciences university freshmen, with 'intention/need related to speciation' being the most common misconception in both samples.

The concept of biotic potential was very difficult to understand for university students in Greece (Athanasiou and Mavrikaki 2014; Lazaridis et al. 2011) and senior pre-service science teachers in Turkey (Tekkaya et al. 2011). By contrast, Flemish (68.5%) and Dutch (74.4%) Veterinary and Biomedical Sciences university freshmen appeared to have a good understanding of this concept (Pinxten et al. 2020). Change in a population, and origin of species were often misunderstood among novice university students in Greece (Athanasiou and Mavrikaki 2014), Veterinary Sciences and Biomedical Sciences university freshmen in Belgium (Pinxten et al. 2020), senior pre-service science teachers in Turkey (Tekkaya et al. 2011), and for primary and lower secondary education in-service teachers in the United Kingdom (Buchan 2019). According to Lazaridis et al. (2011), many biology majors, who actually scored high on the CINS, were not constant in their answers for the same concept.

ECKT

Seven studies (four on pre-, three on in-service teachers) in three European countries (Greece, Serbia, Turkey) used the ECKT (score: 0–2; Rutledge and Warden 2000) or modified versions of this multiple-choice instrument that covers the evolutionary concepts of natural selection, extinction processes, homologous structures, coevolution, analogous structures, convergent evolution, intermediate forms, adaptive radiation, speciation, evolutionary rates, the fossil record, biogeography, environmental change, genetic variability, and reproductive success. Studies revealed that the level of knowledge

[2] Means were calculated for the current review based on the presented data in Venetis and Mavrikaki (2017).

about evolution among science and biology pre-service teachers is very low in both Greece ($M_{biology}$=7.63; Athanasiou et al. 2012) and Turkey ($M_{science}$=7.99; Akyol et al. 2010; $M_{science}$=8.00; Akyol et al. 2012; $M_{biology}$=8.62; Deniz and Sahin 2016). In Turkey, a modified version of the ECKT was used. Akyol et al. (2010) used the modified version by Deniz et al. (2008), while Deniz and Sahin (2016) did not specify the modifications.

In-service teachers' evolution knowledge based on the ECKT ranges from very low (early childhood education) to low (secondary education biology) in Serbia ($M_{early\ childhood}$=7.14, $M_{secondary\ (biology)}$=11.69[3]; Stanisavljevic et al. 2013) and very low (early childhood) to moderate (lower secondary education geology) in Greece[4] ($M_{early\ childhood}$=8.09 – $M_{lower\ secondary\ (geology)}$=14.4; Athanasiou et al. 2016), and low (primary and lower secondary education) in Turkey (M=10.38[5]; Tekkaya et al. 2012). In all three countries, a modified version of the ECKT was used. Athanasiou et al. (2016) modified (details not mentioned) the instrument without excluding any of the 21 items. Tekkaya et al. (2012) used the version modified by Deniz et al. (2008), but included only 19 items. Stanisavljevic et al. (2013) used only 13 items of the original version and changed eight of these items into true/false statements.

KAEVO

Three studies in two European countries (Germany and Slovenia) used the multiple-choice instrument KAEVO that includes the evolutionary concepts: natural selection, biological fitness, speciation, variation, heredity, mutations, phylogenetics, deep time, and human evolution. Based on results of two of these studies (Beniermann 2019; Kuschmierz et al. 2020), secondary school students showed a very low ($M_{grade\ 7}$=1.88, $M_{grade\ 9\text{-}11}$=2.96; score: 0–9; Beniermann 2019; $M_{grade\ 10\text{-}12}$=3.39; score 0–12; Kuschmierz et al. 2020) level of knowledge about evolution in Germany.

Early childhood- and primary education pre-service teachers showed a very low level of evolutionary knowledge in Slovenia (M=3.02[6]; score 0–12; Torkar and Šorgo 2020). Students of different university programs showed low knowledge about evolution (M=5.27; score: 0–9; Beniermann 2019), while biology and non-biology students showed very low knowledge about evolution ($M_{biology}$=4.85, $M_{non\text{-}biology}$=4.31; score: 0–12; Kuschmierz et al. 2020). Despite the fact that biology and non-biology students reached similar levels of knowledge about evolution, the two groups differed significantly from each other (Kuschmierz et al. 2020). Torkar and Šorgo (2020) used eight of twelve items of the KAEVO 2.0, Beniermann (2019) all nine items of KAEVO 1.0.

Beniermann (2019) additionally surveyed German biology teachers in practical training after graduation (in the following added to the group of in-service teachers) who showed moderate knowledge about evolution (M=6.92; Beniermann 2019). In both German studies with the KAEVO, knowledge about evolution was compared between different educational groups and increased with age and educational level (Beniermann 2019; Kuschmierz et al. 2020).

Teleological thinking was the most frequently found misconception in the adaptation items for both the Slovenian sample and German samples. Additionally, in all samples biological fitness was difficult to understand, while a majority of all samples answered an item on heredity of phenotype changes to the direct offspring correctly. In-service biology teachers showed predominantly teleological and anthropomorphic misconceptions, while Lamarckian misconceptions were rather prominent among school students (Beniermann 2019).

KEE

One study on third-year university students in Spain used the multiple-choice instrument KEE (score: 0–10; Moore and Cotner 2009) that covers the following evolutionary concepts: natural selection, biological fitness, evolutionary change, variation. The study revealed low knowledge about evolution for chemistry, history, and English philology students ($M_{chemistry}$=5.2, $M_{history}$=4.8, $M_{english\ philology}$=4.4; Gefaell et al. 2020) and moderate knowledge for biology students (M=6.5; Gefaell et al. 2020).

ORI

Three surveys in two European countries (Germany and Sweden) implemented the ORI (Nehm and Reilly 2007), an open response format instrument on natural selection. Results revealed that university students in Germany and Sweden used randomness and probability (Göransson et al. 2020; Harms and Fiedler 2019) as well as time aspects (Göransson et al. 2020) rarely and inconsistently to explain evolutionary processes. Also, students used evolutionary key concepts to explain evolutionary changes moderately (Harms and Fiedler 2019). A comparison between biology majors and pre-service biology teachers found remarkable deficits in both using

[3] Means were calculated for the current review based on the presented data in Stanisavljevic et al. (2013).

[4] Different interpretation of Athanasiou et al. (2016): low knowledge about evolution for biology and geology teachers; very low for all other groups of teachers.

[5] Mean was calculated for the current review based on the presented data in Tekkaya et al. (2012).

[6] Mean was calculated for the current review based on the presented data in Torkar and Šorgo (2020).

randomness and probability in evolutionary contexts and evolutionary knowledge in general for pre-service biology teachers (Fiedler et al. 2017). Examples of evolutionary adaptation that include the loss of traits seemed to be more challenging for students than examples that include the gain of traits (Göransson et al. 2020).

ACORNS

Two studies (Großschedl et al. 2018; Nehm et al. 2013) in Germany used another open response instrument, the ACORNS (Nehm et al. 2012) on natural selection and non-adaptive change. Großschedl et al. (2018) showed that German secondary education pre-service teachers used significantly more often evolutionary key concepts and significantly less often scientifically inaccurate concepts than primary education pre-service teachers when explaining scenarios in an evolutionary context. According to the authors, the gain of traits was easier to explain in animals than in plants, while for trait loss explanation was easier in plants than in animals (Großschedl et al. 2018). Nehm et al. (2013) compared pre-service biology teachers in Germany, USA, Korea, and Indonesia and found that evolutionary reasoning was similar across the different cultural contexts. Evolution in animals was significantly easier to explain than in plants. In agreement with the previously presented results from Göransson et al. (2020), examples of evolutionary adaptation that include the gain of traits seemed to be easier for students than examples that include the loss of traits (Nehm et al. 2013).

Other instruments

In addition to these repeatedly-used instruments, 16 studies with 16 other instruments on knowledge about evolution have been conducted since 2010 in nine European countries (Croatia, Czech Republic, Germany, Greece, Italy, Slovakia, Slovenia, Switzerland, Turkey). Details of the respective instruments and main results of these studies are summed up in Additional file 4.

Acceptance of evolution

I-SEA

The I-SEA (score 24–120; Nadelson and Southerland 2012), a 24-item 5-point rating scale, includes three subscales on microevolution, macroevolution, and human evolution. The I-SEA was used only once in Europe (the United Kingdom; Betti et al. 2020). Based on the results, most first-year life sciences undergraduate students in the United Kingdom showed high acceptance of evolution, with lower acceptance for human as well as macro- than micro-evolution (M_{total}=93.12, $M_{microevolution}$=96.48, $M_{macroevolution}$=92.88, $M_{human\ evolution}$=92.40; score: 24–120; Betti et al. 2020). In this sample, religiosity was significantly negatively correlated to evolution acceptance, with the lowest acceptance scores for Muslim students, followed by Christians and students of other religions, and highest scores for students with no religion. Biomedical and health students showed significantly lower evolution acceptance than general biology, anthropology or zoology students (Betti et al. 2020).

MATE

The 5-point rating scale MATE includes 20 items on the processes of evolution, the available evidence of evolutionary change, the ability of evolutionary theory to explain phenomena, the evolution of humans, the age of the Earth, the independent validity of science as a way of knowing, and the current status of evolutionary theory within the scientific community (score 20–100; Rutledge and Warden 1999; Rutledge and Sadler 2007). The MATE was used in 20 studies and six European countries (Germany, Greece, Serbia, Spain, Turkey, the United Kingdom) making it the most-often used instrument for measuring evolution acceptance in Europe since 2010. Modified versions with various different numbers of items were used in the United Kingdom (13 items: Mead et al. 2018), Germany (16 items: Lammert et al. 2012), and Turkey (all items on a 4-point rating scale: Deniz and Sahin 2016; 15 items: Irez and Bakanay 2011; 10 items: Yüce and Önel 2015; 18 items: Tekkaya et al. 2012).

Secondary education students showed moderate acceptance of evolution in Germany (M=71.9; Konnemann et al. 2016; M=71.13[7]; Lammert 2012) and high acceptance of evolution in the United Kingdom (no mean value, Mead et al. 2018). Strong believers showed low evolution acceptance in Germany, the influence of the denomination on acceptance was significant, with lowest acceptance scores for Muslims and highest scores for students without a denomination (Lammert 2012). Konnemann et al. (2016) reported that in Germany especially Christian Free Churchers (70.6%), but also Muslims (30.2%) showed low acceptance of evolution, positive attitudes toward the Biblical accounts of creation and a high degree of creationist belief, while unaffiliated showed the highest acceptance of evolution.

Pre-service biology teachers showed low[8] (M=61.06[9]; Deniz and Sahin 2016; $M_{biology}$=59.81[10]; Irez and Bakanay 2011) to moderate acceptance (M=65.52; Deniz

[7] Sum score was calculated for the current review based on the presented data in Lammert (2012).

[8] Different interpretation of Deniz and Sahin (2016): moderate acceptance.

[9] Sum score was calculated for the current review based on the presented data in Deniz and Sahin (2016).

[10] Sum score was calculated for the current review based on the presented data in Irez and Bakanay (2011).

et al. 2011) in Turkey, moderate acceptance in Greece ($M=70.95$; Athanasiou and Papadopoulou 2012; $M=74.45$; Athanasiou et al. 2012), and high evolution acceptance in Germany ($M=84.21$; Großschedl et al. 2014; $M_{primary}=80.55$, $M_{lower\ secondary}=83.52$, $M_{upper\ secondary}=86.63$; Großschedl et al. 2018; $M=82.90$; Nehm et al. 2013). A significant negative correlation for evolution acceptance and religiosity was reported for pre-service biology teachers in Greece (Athanasiou et al. 2012) and Turkey (Deniz et al. 2011; Deniz and Sahin 2016).

Considering pre-service teachers of different fields, these showed low acceptance of evolution[11] in Turkey ($M=57.40$[12]; Bilen and Ercan 2016). Moderate acceptance of evolution was reported for pre-service science teachers in Turkey ($M=66.40$[13]; Akyol et al. 2010). Low acceptance, with even lower acceptance for pre-service science teachers who had previously attended a course on science and nature of science than for students who had not, was reported in Turkey ($M_{attended}=55.38$, $M_{not\ attended}=61.20$; Yüce and Önel 2015[14]). University students in Germany showed high acceptance of evolution for both a treatment and a control group in an interventional study ($M_{treatment}=81.20$, $M_{control}=87.00$; Konnemann et al. 2018). In accordance to that, Spanish third-year university students from different degree programs also showed high acceptance of evolution ($M=87.20$; Gefaell et al. 2020).

In-service teachers' evolution acceptance reached from moderate for primary and secondary education teachers in Turkey ($M=69.60$[15]; Tekkaya et al. 2012) and teachers of early childhood education, primary school and secondary science education in Serbia ($M=76.18$; Stanisavljevic et al. 2013) to high acceptance for primary and lower secondary education teachers in the United Kingdom ($M=85.88$; Buchan 2019) and very high for lower secondary geology teachers in Greece ($M=89.80$; Athanasiou et al. 2016). The range of evolution acceptance among teachers in different fields reached from high to very high in Greece ($M_{early\ childhood}=78.33$, $M_{lower\ secondary\ (geology)}=89.80$; Athanasiou et al. 2016; Katakos and Athanasiou 2020), and from moderate to high in Serbia ($M_{kindergarten}=69.68$, $M_{secondary\ (biology)}=84.56$; Stanisavljevic et al. 2013).

A significant negative correlation for evolution acceptance and religiosity was reported for in-service teachers teaching biology in Greece (Athanasiou et al. 2016).

Other instruments

In addition to these repeatedly-used instruments, 15 studies with 15 other instruments on acceptance of evolution have been conducted since 2010 in 21 European countries (Austria, Cyprus, Denmark, Estonia, Finland, France, Georgia, Germany, Hungary, Italy, Lithuania, Malta, Poland, Portugal, Romania, Russia, Serbia, Spain, Sweden, Turkey, the United Kingdom). Details of the respective instruments and main results of these studies are summed up in Additional file 5.

Correlation between knowledge and acceptance of evolution

We identified 17 studies that reported the relationship between knowledge and acceptance of evolution in six European countries (Germany, Greece, Serbia, Spain, Turkey, the United Kingdom). German secondary education students showed a weak positive correlation between knowledge and acceptance of evolution (grade 9–11, Beniermann 2019; grade 9–10, Lammert 2012). Beniermann (2019) also found a weak positive correlation between knowledge and acceptance of evolution for university students. Likewise, pre-service teachers showed a weak positive correlation between knowledge and acceptance of evolution in Germany (Graf and Soran 2010; Großschedl et al. 2014), Turkey (Akyol et al. 2012), and Greece (Athanasiou et al. 2012). Additional studies in Germany (Großschedl et al. 2018; Nehm et al. 2013) and Turkey (Deniz and Sahin 2016) revealed a moderate positive correlation for pre-service teachers. Also, a moderate positive correlation for in-service teachers was found in Germany (Beniermann 2019[16]), Serbia (Stanisavljevic et al. 2013) and the United Kingdom (Buchan 2019).

By contrast, some studies did not find significant correlations between knowledge and acceptance of evolution. This was the case for primary and lower secondary education students in Germany (grade 7, Beniermann 2019; grade 5–6, Fenner 2013), psychology students (Annaç and Bahçekapili 2012) and pre-service teachers in Turkey (Akyol et al. 2010; Graf and Soran 2010), third-year university students of different fields in Spain (Gefaell et al. 2020) and in-service teachers in Greece (Athanasiou et al. 2016) and Turkey (Tekkaya et al. 2012).

[11] Different interpretation of Bilen and Ercan (2016): undecided position about evolution.

[12] Sum score was calculated for the current review based on the presented data in Bilen and Ercan (2016).

[13] Sum score was calculated for the current review based on the presented data in Akyol et al. (2010).

[14] Sum scores were calculated for the current review based on the presented data in Yüce and Önel (2015).

[15] Sum score was calculated for the current review based on the presented data in Tekkaya et al. (2012).

[16] Trainee biology teachers.

Discussion

The diversity of the instruments used to assess acceptance of evolution and knowledge about evolution in Europe makes the comparison within and between countries and educational groups rather complicated or even questionable regarding its validity. Another crucial point in this regard is the often lacking evidence for local validity and reliability that was discovered in the present review (see Additional files 3, 4, and 5). Moreover, only five of the 13 most commonly used instruments (Mead et al. 2019) were found to have been applied to European samples (ACORNS, CINS, I-SEA, KEE, MATE): this may be partly explained by the fact that some instruments have been only recently developed and published (as is the case for CANS and GAENE). This, along with a generally low number of studies per country across Europe (both as regards knowledge and acceptance of evolution, see Fig. 1 and 2) indicate that much more research is still needed i) to expand and diversify samples, ii) to unify already available ones and compare among them and iii) to apply standards to provide appropriate sources of evidence for reliability and validity. This way it will be possible to get a clearer picture of the European educational context and to make sound and reliable inferences on how different instructional settings impact learning.

Having these methodological limitations in mind (see paragraph on validity issues for a deepened discussion), our results show that the current state of research regarding knowledge and acceptance of evolution of students and teachers in Europe is diverse. However, there are in particular some major points of concern that emerge from our results. As we detail below, pre-service teachers show low to moderate levels of knowledge about evolution in some samples of several European countries (Turkey, Germany, Greece, Slovenia, Czech Republic, Slovakia). In some surveyed samples (Greece and Turkey), undecided attitudes or even rejection of evolution are recorded. As regards knowledge about evolution of primary education in-service teachers, scores range unsatisfyingly from very low to moderate. Teachers, and in particular biology teachers, play a key role in correcting misleading notions and conceptual schemas of evolution from the early stages of education, adjusting instruction to respond to their students' inquiries and needs. The persistence of various misconceptions through all educational stages that we found in our study must be interrogated by future research also in light of these critical aspects, along with a more detailed understanding of the educational offer about evolution across various curricula.

Knowledge about evolution

School students

The level of knowledge about evolution in European school students has not been much explored yet. The present review resulted in ten publications in six European countries on the assessment of early childhood, primary and secondary education students' knowledge about evolution (Croatia and Slovenia: Kralj et al. 2018; Germany: Beniermann 2019; Fenner 2013; Jördens et al. 2016; Kuschmierz et al. 2020; Lammert 2012; Greece: Kampourakis et al. 2012a, b; Italy: Kampourakis et al. 2012a, b; Switzerland: Queloz et al. 2017), gathered with eight different instruments (KAEVO and self-developed). In summary, the data on knowledge about evolution in European school students is limited and not unified. The current state of research reveals mixed levels of knowledge about evolution for secondary education students, from very low (Beniermann 2019; Kuschmierz et al. 2020), moderate (Fenner 2013; Lammert 2012) to high (Rufo et al. 2013). Furthermore, a variety of misconceptions, predominantly teleological and Lamarckian, for primary (e.g., Kampourakis et al. 2012a, b) and secondary education students of various grades (e.g., Beniermann 2019; Fenner 2013; Fischer 2014; Jördens et al. 2016; Lammert 2012; Queloz et al. 2017) is apparent. The persistence of such misconceptions might indicate that European school curricula may not fully succeed in coping with naïve conceptual frameworks (that are known to develop at an early age). Also, the knowledge displayed by pre-service and in-service teachers plays a significant role in this regard. Critical aspects have emerged in this sense (see sections below).

University students

Overall, eight studies on university students (excluding pre-service teachers) in seven countries (Flanders, Belgium: 1; Germany: 3; Greece: 2; the Netherlands: 1; Spain: 1; Sweden: 1; Turkey: 1) were discovered, gathered with four different instruments (CINS, KAEVO, KEE, and ORI). Knowledge about evolution of university students seems to be an issue (low to moderate knowledge about evolution or frequently occurring misconceptions) in several countries: Turkey (Annaç and Bahçekapili 2012), Germany (Beniermann 2019; Fiedler et al. 2017; Göransson et al. 2020; Harms and Fiedler 2019; Kuschmierz et al. 2020), Greece (Athanasiou and Mavrikaki 2014), Spain (Gefaell et al. 2020), and Sweden (Göransson et al. 2020).

The level of knowledge about evolution of European university students varies between and within the different fields of study. Knowledge about evolution was very low (Germany: English language and literature, and mathematics students, Kuschmierz et al. 2020; Turkey: psychology majors, Annaç and Bahçekapili 2012) and low (Germany: different study programs, Beniermann 2019; Spain: chemistry, history, and English philology students, Gefaell et al. 2020) in university students from different non-biology related study programs. Biology-related university freshmen showed low knowledge about evolution (Belgium: Pinxten et al. 2020). Biology majors showed very low (Germany: Kuschmierz et al. 2020), moderate (first- to third-year and postgraduate biology majors, Greece: Athanasiou and Mavrikaki 2014; Spain: Gefaell et al. 2020) to rather high knowledge about evolution (fourth-year biology majors, Greece: Athanasiou and Mavrikaki 2014; Lazaridis et al. 2011). The finding of Nehm and Ha (2011) for university students in the USA that examples of evolutionary adaptation including the loss of traits are more challenging than examples that include the gain of traits, was also confirmed for German university students (Göransson et al. 2020).

Misconceptions, predominantly teleological misconceptions, were also present among university students of different fields of study (Athanasiou and Mavrikaki 2014; Beniermann 2019; Kuschmierz et al. 2020; Pinxten et al. 2020). Also, some evolutionary concepts, as for example 'biotic potential' (Athanasiou and Mavrikaki 2014; Lazaridis et al. 2011), change in a population, and origin of species (Athanasiou and Mavrikaki 2014; Pinxten et al. 2020) seemed to be difficult to understand across multiple samples. Summed up, it can be stated that the knowledge about evolution increased with biology education level across different European university student samples.

Pre-service teachers

Pre-service teachers, especially future biology teachers, play a special role in terms of knowledge about evolution and are the most assessed group of university students in this regard, with numerous studies in Turkey (Akyol et al. 2010, 2012; Deniz and Sahin 2016; Graf and Soran 2010; Keskin and Köse 2015; Tekkayaet al. 2011) and Germany (Fiedler et al. 2017; Graf and Soran 2010; Großschedl et al. 2018; Nehm et al. 2013). Pre-service teachers showed low to moderate knowledge in Turkey and low to rather high knowledge in Germany. In other countries, the database is very thin or no publications were found. Overall, 15 studies on pre-service teachers were discovered in six countries (Czech Republic: 1; Germany: 6; Greece: 2; Slovakia: 1; Slovenia: 2; Turkey: 7), gathered with ten different instruments (CINS, ECKT, KAEVO, ORI, ACORNS, and self-developed).

With this in mind, the results for pre-service teachers show partly alarmingly low levels of knowledge about evolution. Knowledge about evolution of pre-service teachers seems to be an issue (low to moderate knowledge about evolution or frequently occurring misconceptions) in several countries: Turkey (Akyol et al. 2010, 2012; Deniz and Sahin 2016; Graf and Soran 2010; Keskin and Köse 2015; Šorgo et al. 2014; Tekkaya et al. 2011), Germany (Beniermann 2019; Fiedler et al. 2017; Graf and Soran 2010), Greece (Athanasiou et al. 2012; Athanasiou and Mavrikaki 2014) Slovenia (Šorgo et al. 2014; Torkar and Šorgo 2020); Czech Republic (Šorgo et al. 2014); and Slovakia (Šorgo et al. 2014). Pre-service teachers of different fields showed very low knowledge about evolution in two studies (Greece: Athanasiou and Mavrikaki 2014; Slovenia: Torkar and Šorgo 2020), low knowledge in two studies (Germany and Turkey: Graf and Soran 2010; Greece: Athanasiou and Mavrikaki 2014), and moderate knowledge in one study (Nehm et al. 2013). Studies that focused on pre-service science or pre-service biology teachers revealed a variety of knowledge about evolution, from unexpectedly very low (Greece: Athanasiou et al. 2012; Turkey: Akyol et al. 2010; Akyol et al. 2012; Deniz and Sahin 2016), low (Turkey: Tekkaya et al. 2011), to moderate (Germany: Nehm et al. 2013; primary and lower secondary education, Großschedl et al. 2018), and rather high knowledge about evolution (Germany: upper secondary education, Großschedl et al. 2018). Results from open response instruments confirmed that the context effects in evolution assessment found in European university students (Göransson et al. 2020), were also present in pre-service teachers. The examples of evolutionary adaptation in animals apparently were easier to explain than examples in plants (Großschedl et al. 2018; Nehm et al. 2013). The same effect was found for examples including the gain of traits in contrast to the loss of traits (Großschedl et al. 2018; Nehm et al. 2013). These results indicate that the ratio of gain/loss and animal/plants items in an instrument will control measurement outcome to a large degree, which should be taken into account in future standardized assessments across Europe (see also Nehm et al. 2012).

Misconceptions, predominantly teleological misconceptions, were also present among pre-service teachers (Germany: Graf and Soran 2010; Greece: Athanasiou and Mavrikaki 2014; Turkey: Keskin and Köse 2015; Tekkaya et al. 2011; Slovenia: Torkar and Šorgo 2020). In contrast to other university students, knowledge about evolution did not consistently increase with biology education level across different European pre-service teacher samples.

In-service teachers

Seven studies on in-service teachers were found in four countries (Greece: 4, Serbia: 1, Turkey: 1, the United Kingdom: 1), gathered with four different instruments (CINS, ECKT, self-developed). Very low (Greece:

Athanasiou et al. 2016; Serbia: Stanisavljevic et al. 2013), low (Greece: Athanasiou et al. 2016; Prinou et al. 2011; Stasinakis and Athanasiou 2016; Serbia: Stanisavljevic et al. 2013; Turkey: Tekkaya et al. 2012) or moderate (Greece: Athanasiou et al. 2016; United Kingdom: Buchan et al. 2019) knowledge about evolution was reported for different groups of in-service teachers in several countries.

The level of knowledge about evolution among in-service teachers differed according to the type of school education. While very low knowledge about evolution was stated for early childhood education (Greece: Athanasiou et al. 2016; Serbia: Stanisavljevic et al. 2013), primary education teachers showed very low (Serbia: Stanisavljevic et al. 2013), low (Greece: Athanasiou et al. 2016; Turkey: Tekkaya et al. 2012), and moderate knowledge about evolution (the United Kingdom: Buchan 2019). Very low (physics, Serbia: Stanisavljevic et al. 2013), low (biology, chemistry, Serbia: Stanisavljevic et al. 2013; Turkey: Tekkaya et al. 2012), moderate (Greece: Athanasiou et al. 2016; the United Kingdom: Buchan 2019) and rather high (Greece: Venetis K, Mavrikaki E. Oi gnoseis ton ekpaideytikon thetikon epistimon shetika me tous exeliktikous mixanismous ton zontanon organismon. Sto A. Polyzos, L. Anthis (epim.), Praktika Ergasion 4th Panelliniou Synedriou "Biologia stin Ekpaideysi" [Knowledge of secondary education science teachers regarding the evolutionary mechanisms of living organisms. In: Polyzos A, Anthis L, editors. Proceedings of the 4th Panhellenic Conference "Biology in Education"]. Piraeus: Panhellenic Association of Bioscientists 2017) to high (Greece: only biologists, Venetis et al. 2017) knowledge about evolution was also presented for secondary education teachers. Even in-service teachers showed mainly teleological misconceptions (United Kingdom: Buchan 2019; Greece: Prinou et al. 2011), and also anthropomorphic and Lamarckian misconceptions (United Kingdom: Buchan 2019). This illustrates the persistence of misconceptions through all education levels that is likely to affect the quality of evolution instruction offered to the various groups of students.

Cross-country studies

Five publications include samples from two or more European countries, four of them compare two countries in terms of knowledge about evolution (Croatia and Slovenia: Kralj et al. 2018; Germany and Turkey: Graf and Soran 2010; Belgium and the Netherlands: Pinxten et al. 2020) or with a focus on misconceptions (Germany and Sweden: Göransson et al. 2020; Belgium and the Netherlands: Pinxten et al. 2020). One study compares four countries regarding knowledge about evolution (Czech Republic, Slovakia, Slovenia, and Turkey: Šorgo et al. 2014).

Altogether, results of 15 different European countries on evolutionary knowledge were documented in the current review. In only three of these countries three or more publications are discovered (Germany: 11, Greece: 7, Turkey: 9; see Fig. 1). This implies that there is only few or even no information available concerning knowledge about evolution in most European countries. Thus, evolution education research in Europe should fill this gap in the future by conducting cross-country studies on a comparable target group by use of the same instrument and providing evidence for local validity.

Acceptance of evolution

School students

Our review resulted in ten studies focusing on acceptance of evolution of school students that were discovered in six countries (Austria: 1, France: 1; Germany: 5, Italy: 1, Turkey: 1, the United Kingdom: 1), gathered with eight different instruments (MATE and self-developed).

Evolution acceptance in school students is rather high in three European countries (Germany: Beniermann 2019; Fenner 2013; Konnemann et al. 2016; the United Kingdom: Mead et al. 2018; Italy: Rufo et al. 2013). In three countries, studies reported moderate acceptance (Germany: Konnemann et al. 2016; Lammert 2012), mixed attitudes towards evolution (Austria: Eder et al. 2011) or even rejection (Turkey: Köse 2010) for this sampling group. The conflicting results for Germany support an issue, which has also been found in previous studies (e.g., Barnes et al. 2019; Mead et al. 2019; Smith et al. 2016): besides other reasons, the application of different measuring instruments can lead to inconsistent results. Konnemann et al. (2016) used a self-developed instrument as well as the MATE, reporting moderate acceptance of evolution for the MATE and at the same time positive attitudes towards evolution for a great majority of the students (87.6%) based on the self-developed instrument. In both studies that revealed moderate acceptance (Konnemann et al. 2016; Lammert 2012), the MATE was used. Beniermann (2019) and Fenner (2013), who reported rather high acceptance, used self-developed measurement instruments.

The results show that only a few school students in Europe seem to reject evolution. Predominant rejection occurred only in one Turkish study (Köse 2010), where evolution was recently banned from textbooks (Genç 2018). Although there is only one study on Turkish school students, the results shown by Köse (2010) are in accordance with results of studies on Turkish pre-service teachers (e.g., Akyol et al. 2012; Deniz and Sahin 2016; Graf and Soran 2010).

University students

Only five studies on university students who are not pre-service teachers, were reported in four countries (Germany, Spain, Turkey, and the United Kingdom), gathered with five instruments (I-SEA and self-developed). According to the authors, in all samples surveyed students largely accept evolution (Germany: Beniermann 2019; Spain: Gefaell et al. 2020; Turkey: Annaç and Bahçekapili 2012; the United Kingdom: Betti et al. 2020; Southcott and Downie 2012). Despite the fact that this is generally good news, the explanatory power of a total of five studies is pretty low. More research on university students would be necessary to strengthen this tendency.

Furthermore, a crucial point when comparing studies using different instruments, is the categorization of the mean scores. For example, Annaç and Bahçekapili (2012) reported a "high acceptance" for a mean score that reflects a low to moderate acceptance of evolution based on the MATE scale (see Table 2). This issue displays that it is important to standardize comparative studies across countries.

Pre-service teachers

Fifteen studies on pre-service teachers' acceptance of evolution were discovered in four countries (Germany: 5, Greece: 2, Turkey: 7, the United Kingdom: 1), gathered with three different instruments (MATE and self-developed).

In contrast to the other university students, many studies have been conducted on European pre-service teachers. Additionally, the situation is more diverse than for school students and other university students. In some countries, the surveyed samples largely accept evolution (Germany: Graf and Soran 2010; Großschedl et al. 2014; Großschedl et al. 2018; Konnemann et al. 2018; Nehm et al. 2013; the United Kingdom: Arthur 2013), in some countries the surveyed samples have undecided positions or rather reject evolution (Greece: Athanasiou and Papadopoulou 2012; Athanasiou et al. 2012; Turkey: Akyol et al. 2010, 2012 Deniz et al. 2011; Deniz and Sahin 2016; Graf and Soran 2010; Irez and Bakanay 2011; Bilen and Ercan 2016; Yüce and Önel 2015). These alarming results for Greece and Turkey should be investigated further, especially in view of the particularly important role of pre-service teachers in evolution education. In both countries, evolution only plays a minor role in school curricula.

In-service teachers

Seven studies on in-service teachers' acceptance of evolution were found in four countries (Greece: 1, Serbia: 1, Turkey: 1, the United Kingdom: 2), gathered with two different instruments (MATE and self-developed). In almost all of these countries, in-service teachers showed moderate (Serbia: Stanisavljevic et al. 2013; Turkey: Tekkaya et al. 2012) to high acceptance (Germany: Beniermann 2019; Greece: Athanasiou et al. 2016; Serbia: Stanisavljevic et al. 2013; the United Kingdom: Buchan 2019; Downie et al. 2018). In one study, the majority of biology teachers rejected evolution (Turkey: Köse 2010). Despite the crucial importance of in-service teachers to foster knowledge about evolution and acceptance of evolution, the amount of studies in Europe is quite low. The partly alarming results concerning pre-service teachers in the present review lead to the assumption that this issue could arise also in future studies on in-service teachers in Europe.

Comparing acceptance among different education levels, a rejection of evolution was mainly found in university students, but rather not in school students and in-service teachers (but see Köse 2010). Comparable with the topic of knowledge about evolution, the number of studies in different countries varied among European countries. Much research has been conducted in Turkey (especially for university students) and Germany. In all other countries, a sharp image of evolution acceptance is missing. Only two publications compare acceptance of evolution among European countries by means of the same instrument within comparable groups (Clément 2015a; Graf and Soran 2010).

Results of 35 different European countries on evolution acceptance were documented in this article. An amount of three or more publications are found in only four of these countries (Germany: 9, Greece: 3, and Turkey: 10, the United Kingdom: 6; see Fig. 2). Similar to evolutionary knowledge, it has been shown that there is only few or even no information available about acceptance of evolution in most European countries.

Relationship between acceptance of evolution and knowledge about evolution

European studies that investigated both acceptance of and knowledge about evolution reported very different results concerning the existence and strength of the relationship between these factors. However, some trends are visible, for example the lacking or weak correlation between acceptance and knowledge for primary and secondary school students in Germany indicating an increase of strength of the relationship the higher the educational level (Beniermann 2019; Fenner 2013; Lammert 2012). This assumption is supported by the fact that based on the same instruments (ATEVO and KAEVO) Beniermann (2019) showed an increase of the correlation coefficient from lower secondary students to in-service biology teachers. Other studies on pre-service or in-service teachers in Europe showed weak (Germany: Graf and Soran 2010; Großschedl et al. 2014; Turkey: Akyol et al. 2012; Greece: Athanasiou et al. 2012) or moderate (Germany: Großschedl et al. 2018; Nehm et al. 2013; Turkey: Deniz and Sahin 2016; Serbia: Stanisavljevic et al. 2013; the United Kingdom: Buchan 2019) positive relationships between acceptance and knowledge. Based on these results there is no effect of the used instruments visible as the mentioned studies applied either a combination of the MATE and the ECKT or utilized the MATE and the CINS. Both combinations of instruments lead to weak as well as moderate positive correlations between acceptance and knowledge.

However, in contrast to these results, there are contradicting studies reporting no significant correlation for pre-service and in-service teachers in Turkey (Akyol et al. 2010; Graf and Soran 2010; Tekkaya et al. 2012) and Greece (Athanasiou et al. 2016). Except for Graf and Soran (2010) who used deviant instruments, all of these studies used a combination of ECKT and MATE to assess knowledge and acceptance. Even though the combination of ECKT and MATE for almost all non-significant correlations is noteworthy, it should be considered that for a valid comparison between combinations of instruments, these instruments should be applied to comparable or ideally the same samples.

Overall, the results emphasize the difference between knowledge about evolution and accepting evolution as two separate constructs, since there is no clear connection between these two variables visible. This once more demonstrates the importance for measuring instruments that clearly distinguish between acceptance of evolution and knowledge about evolution, as discussed in several methodological considerations (Beniermann 2019; Kahan 2015; Konnemann et al. 2012; McCain and Kampourakis 2018; Roos 2014; Smith 2010).

Based on this review, the relation between acceptance of evolution and knowledge about evolution remains open (see Barnes et al. 2019; Dunk et al. 2019) to investigation in Europe and needs a more standardized way to assess both factors allowing for a more comparable database.

Religiosity and other factors influencing acceptance of evolution

As a negative relation between religious faith and acceptance of evolution was discovered for primary and secondary education students (Eder et al. 2011; Lammert 2012), university students (Annaç and Bahçekapili 2012; Beniermann 2019; Betti et al. 2020; Graf and Soran 2010; Southcott and Downie 2012) including biology pre-service teachers (Athanasiou et al. 2012; Deniz et al. 2011; Deniz and Sahin 2016) as well as in-service teachers (Athanasiou et al. 2016; Clément et al. 2012) across European countries, the close relationship between these constructs becomes visible. However, it was shown before in the USA (McCain and Kampourakis 2018) as well as Europe (Germany, Beniermann 2019) that religious faith alone is no predictor for a rejection of evolution and a huge percentage of religious believers do accept evolution.

Acceptance of evolution differed between denominations for primary and secondary education students, as well as university students in Austria, Germany and the UK with lowest acceptance scores for Muslims (Eder et al. 2011; Fenner 2013; Lammert 2012; Southcott and Downie 2012) or Christian Free Churchers (Beniermann 2019; Konnemann et al. 2016) and highest scores for students without a denomination (Beniermann 2019; Lammert 2012; Konnemann et al. 2016). It should be emphasized that, subsamples of Muslims and Christian Free Churchers in European samples are normally very small and therefore difficult to generalize.

Clément (2015a) and Clément et al. (2012) showed how in-service teachers in Europe differed concerning their acceptance of evolution depending on the predominant affiliation in the country samples. For example, Orthodox teachers in Russia showed the most creationist positions (Charles and Clément 2018) and European countries with a large share of Catholic (Poland, Malta) or Orthodox (Georgia, Romania) respondents tend to reject evolution more often (Clément 2015a). However, in their cross-country comparison Clément et al. (2012) showed that even countries with a comparable share of Orthodox teachers as members of a conservative religion (Cyprus, Georgia, Romania and Serbia) differ highly in their creationist positions (between 54% in Georgia and 11% in Serbia). Clément (2015a) concluded that the observed differences between countries are mostly related to the countries and not to the denomination: *"Globally, in the less economically developed countries, teachers are more believing in God and practicing their religion, whatever is this religion, and they are more creationist and more often against a separation between science and religion"* (Clément 2015a, p. 286). Although some religious affiliations are important parts of several national backgrounds, they cannot be separated from other important factors like national history, politics and economy (Clément 2015b). This *"strong influence of the national socio-cultural context"* (Clément et al. 2012) was also confirmed by comparison of Catholic, Protestant and Muslim teachers in different countries (Clément 2015a).

Another important path of investigation for future research within Europe consists in assessing which factors mainly influence the acceptance of evolution. Besides religiosity, conceptions on the nature of science (NOS; Smith 2010; Smith and Siegel 2004)—generally regarded as fundamental components of scientific literacy—may also play a critical role in this sense. Akyol et al. (2010) as well as Graf and Soran (2010) identified a statistically significant positive contribution of understanding of the nature of science to the acceptance of evolution among pre-service teachers. Moreover, attitudes towards science have found to be a significant predictor for acceptance of evolution for German (Graf and Soran 2010; Großschedl et al. 2014) and Turkish (Graf and Soran 2010) pre-service teachers. Therefore, future studies should further explore the correlation between understanding the nature of science (in its epistemological and sociological aspects), attitudes towards science and acceptance of evolution in Europe.

Cross-country studies

Overall, in only four studies samples from more than one country were surveyed in terms of acceptance of evolution and/or knowledge about evolution (Clément 2015a; Göransson et al. 2020; Graf and Soran 2010; Pinxten et al. 2020; Šorgo et al. 2014). Even if the results of Clément (2015a) are based on several multiple-choice questions and no established measurement instrument, they show that teachers' views on evolution and religiosity are highly connected to their national socio-cultural background.

Numerous studies have been conducted in only a few countries (mainly Greece, Turkey, and Germany). Very few instruments have been used multiple times and the target groups are very diverse. Further research will be necessary to get a clear overview of the status of knowledge and acceptance of evolution among different education levels in Europe.

Summed up, a comprehensive overview of knowledge and acceptance of evolution in Europe, conducted with a comparable sample and the same high-quality instrument in each country, is still missing.

Measuring instruments

The identified instruments to measure knowledge about evolution and attitudes towards evolution in European studies focus on different aspects of the target construct. Especially the instruments that aim to measure knowledge about evolution differ concerning the evolutionary concepts they cover (e.g., KAEVO vs. CINS).

With regard to measuring acceptance of evolution, Barnes et al. (2019) already showed in a comparative analysis that different approaches in some cases lead to different results and hence different interpretations. In a German sample, Konnemann et al. (2016) also obtained diverging results based on two different measures. However, even globally there are still only few publications that investigated whether different instruments result in different conclusions about attitudes towards evolution (Barnes et al. 2019; Metzger et al. 2018; Rachmatullah et al. 2018; Romine et al. 2018; Sbeglia and Nehm 2018, 2019) and even these comparative studies came to different conclusions. For example, Romine et al. (2018) concluded that the MATE, GAENE, and I-SEA can be considered as a single scale to measure one or two factors without losing quantitative interpretability, while Barnes et al. (2019) emphasized the partly inconsistent results based on different instruments by use of the I-SEA, GAENE, MATE and the *100-point instrument of self-defined acceptance*. These inconsistent results were mostly visible for Christian and Mormon respondents. However, these differences in results occurred not for all instruments and not between all groups. The effect of different instruments was mainly visible when focusing on the effect of evolution understanding on evolution acceptance. For this relationship, evolution understanding was a better predictor, when evolution acceptance was assessed based on the MATE or the I-SEA microevolution scale. When people identified as Protestant or Mormon, measured values for acceptance of evolution differed depending on the applied instrument.

These reported inconsistent results may be partly explained by the different focus on evolution in general, microevolution, macroevolution or human evolution (Barnes et al. 2019), since several studies in the US showed that levels of acceptance are higher for microevolution than for macroevolution or human evolution (Barnes et al. 2019; Nadelson and Hardy 2015; Nadelson and Southerland 2012). Theoretically, human evolution as well as macroevolution are in conflict with many religious beliefs, while even creationists accept microevolution to some extent (Pobiner 2016; Scott 2008). In Europe this difference was visible in the only study that used the I-SEA (Betti et al. 2020). Furthermore, one European study emphasized the lower acceptance for evolution of the human mind compared to evolution in general (Beniermann 2019).

Another crucial factor regarding the decision for one instrument to measure acceptance of evolution in Europe is the distinction between acceptance of evolution and religious belief. The framing of questions on attitudes towards evolution is of crucial importance, since the way in which the relationship of evolution, faith and creationism is presented, will influence the results of a survey (Elsdon-Baker 2015; Kampourakis and Strasser 2015). While Romine et al. (2017)argued for the US context that the inclusion of explicitly creationist views in assessments of acceptance of evolution may not be a problem, McCain and Kampourakis (2018) showed that publication polls about the acceptance of evolution lead to different results, depending on the inclusion of a statement about God in the questions about evolution. This distinction may be even more important, when investigating the relationship between acceptance of evolution and religious faith in less religious countries (Beniermann 2019), as it is the case in several European countries (Clément 2015a).

The diversity of the instruments used to assess acceptance of evolution and knowledge about evolution in Europe is one major point that makes the comparison within and between educational groups and countries rather complicated or even questionable regarding its validity. One approach to address this issue is to build categories of acceptance and knowledge levels to compare between results derived from different instruments. Most published scales do not recommend categories for interpretation of survey results, so that authors of single studies apply categories (e.g., "low knowledge", "moderate acceptance") themselves. This approach serves standardization between studies, even if our standardized categories are in some cases in conflict with interpretation of study authors.

Validity issues

In total, 26 studies in this review used their own instruments to assess acceptance or knowledge about evolution, making it more difficult to compare results between studies. In addition to studies that used previously published instruments, 31 other instruments were used to assess acceptance or knowledge about evolution in Europe since 2010. Most likely, not all of these instruments have undergone a validation procedure (e.g., based on AERA 2014). The literature review demonstrates that evidence for validity and reliability is at least often not reported in these publications: Only six of the 15 studies identified in the present review that used an own instrument to assess acceptance of evolution provided at least one source of evidence for validity of the instrument (see Additional file 5). For non-established instruments to assess knowledge about evolution nine studies reported at least one source of evidence for validity while seven studies did not provide any evidence (see Additional file 4).

However, there are even validity issues for most of the published scales (Mead et al. 2019), not to mention local validity for the respective studies that used these instruments (see Additional file 3). The present review showed that six of nine studies that used the CINS in a European context did not report any source of evidence for local validity of the CINS within their setting. Those who provided evidence for validity reported results for PCA (internal structure; Athanasiou and Mavrikaki 2014; Pinxten et al. 2020) or referred to an expert review (content validity; Tekkaya et al. 2011). Evidence for reliability in form of internal consistency was reported for five of the nine studies. Altogether, four of these nine studies did neither provide evidence for validity nor for reliability (Annaç and Bahçekapili 2012; Buchan 2019; Lazaridis et al. 2011; Nehm et al. 2013).

The majority of studies utilizing the ECKT did not provide any evidence for validity. Only one out of seven studies reported results for dimensionality (Akyol et al. 2012). In four of the seven studies evidence for reliability was provided via internal consistency (Akyol et al. 2012; Athanasiou et al. 2012, 2016; Tekkaya et al. 2012). Summed up, in three studies neither evidence for validity nor for reliability was provided (Akyol et al. 2010; Deniz and Sahin 2016; Stanisavljevic et al. 2013).

Two of three studies using the KAEVO reported multiple evidence for validity (content validity, internal structure) and reliability (Beniermann 2019; Kuschmierz et al. 2020). One study did not provide any evidence neither for validity nor for reliability (Torkar and Šorgo 2020). Gefaell et al. (2020), who used the KEE, provided one source of evidence for validity (external structure) and reliability (internal consistency). One of three studies using the ORI provided evidence for validity (content validity; Göransson et al. 2020). Göransson et al. (2020) and also one additional study provided evidence for reliability (Fiedler et al. 2017). None of the two studies using the ACORNS provided evidence for validity but both studies provided evidence for reliability (Großschedl et al. 2018; Nehm et al. 2013).

Betti et al. (2020) provided evidence for validity (internal structure) but not for reliability using the I-SEA. Seven of 21 studies using the MATE provided evidence for local validity via internal structure or content validity and reliability (Akyol et al. 2012; Großschedl et al. 2014; Irez and Bakanay 2011; Konnemann et al. 2016; Lammert 2012; Tekkaya et al. 2012; Yüce and Önel 2015). Almost all studies (18) provided evidence for reliability, predominantly via internal consistency (Akyol et al. 2010, 2012; Athanasiou and Papadopoulou 2012; Athanasiou et al. 2012, 2016; Bilen and Ercan 2016; Denizet al. 2011; Deniz and Sahin 2016; Gefaell et al. 2020; Großschedl et al. 2014, 2018; Irez and Bakanay 2011; Konnemann et al. 2016, 2018; Lammert 2012; Mead et al. 2018; Tekkaya et al. 2012; Yüce and Önel 2015). Only three studies provided no evidence for neither reliability nor local validity (Buchan 2019; Nehm et al. 2013; Stanisavljevic et al. 2013).

The importance of providing evidence for local validity and reliability arised in the field of evolution education within the last 12 years (Mead et al. 2019; Nehm and Schonfeld 2008; Smith et al. 2016). Thus, the awareness about the necessity to provide proper evidence for local validity and reliability steadily increased over the years.

However, even studies that were published within the last 2 years are in some cases lacking evidence of local validity and reliability.

Furthermore, most published scales have been developed and validated for specific target groups, but are often used for different groups (e.g., different educational levels), even if it is questionable whether they are suitable for these groups (e.g., for MATE: Wagler and Wagler 2013). However, particularly in case of knowledge instruments, this raises the question, whether categories for interpretation of results should be adjusted when applying the same instrument for different educational levels. To date, there are only few instruments that have been developed for multiple education levels (e.g., KAEVO and MATE).

Conclusions

The current state of research regarding knowledge and attitudes of evolution of students and teachers in the different European countries varies greatly in terms of number of publications and used instruments. Many different instruments have been used, most of the established instruments only rarely, in parts or in modified versions. Regardless of whether established instruments, self-developed or only locally distributed instruments were utilized, only about one-third of all studies on acceptance and/or knowledge about evolution provided evidence for local validity and reliability. Additionally, very few studies compared similar target groups in two or more European countries.

This situation makes it urgent that further research is needed to obtain a comprehensive overview of the state of knowledge about evolution and acceptance of evolution in the different educational settings in Europe. The available database is not sufficient to compare European countries reliably. The science education community should aim for standardized assessment of acceptance and knowledge about evolution in comparable target groups in many different European countries to address the investigation of how the various cultural backgrounds as well as different school systems within Europe may lead to differences in acceptance and understanding of evolution. In terms of acceptance, besides the national socio-cultural context and denominations, curricula seem to play a major role in this case, as a lack of evolution in curricula tended to be associated with a rejection of evolution in some countries.

Additionally, future research should also attempt to explain what underlies the worrying persistence of misconceptions through all European educational levels that our results have highlighted. Fostering conceptual change, instead of simply adding on existing knowledge, are held by some to be major goals of education (Sinatra et al. 2008). Drawing causal and comparative inferences will only be possible after a rigorous assessment of how much and how well European school curricula cover evolution (as pursued by EuroScitizen COST Action (CA17127)).

We emphasize standardized research on European evolution education settings and subsequently develop ways for not only sound investigation and proper reporting of evolutionary knowledge and acceptance of evolution, but furthermore evidence-based teaching of evolution.

Supplementary information

Supplementary information accompanies this paper at https://doi.org/10.1186/s12052-020-00132-w.

Additional file 1. Commonly used measuring instruments for knowledge and acceptance of evolution based on Mead et al. (2019).

Additional file 2. Means and categories per publication using frequently used instruments, sorted by specific instrument.

Additional file 3. Sample details per publication using the frequently used instruments, sorted by specific instrument.

Additional file 4. Details of European studies on knowledge about evolution using instruments, other than the established instruments.

Additional file 5. Details of European studies on acceptance of evolution using instruments, other than the established instruments.

Abbreviations

ACORNS: Assessing COntextual Reasoning about Natural Selection; ATEVO: Attitudes Towards EVOlution; ATEEK: Assessment Tool for Evaluating Evolution Knowledge; BCI: Biological Concepts Instrument; BIOHEAD-Citizen project: Biology, Health and Environmental Education for better Citizenship; CANS: Concept Assessment of Natural Selection; CINS: Conceptual Inventory of Natural Selection; EALS: Evolutionary Attitudes and Literacy Survey; ECKT: Evolution Content Knowledge Test; ECT: Evolution Concept Test; EvoDevoCI: understanding of basic concepts of Evolutionary Developmental Biology Instrument; FOWID: Research Group on Worldviews in Germany (Forschungsgruppe für Weltanschauungen in Deutschland); GAENE: Generalized Acceptance of Evolution Evaluation; GeDI: Genetic Drift Inventory; I-SEA: Inventory of Student Evolution Acceptance; ISCED: International Standard Classification of Education; KAEVO: Knowledge About EVOlution; KEE: Knowledge of Evolution Exam; KiL project: Interdisciplinary project named "Measuring the professional knowledge of preservice mathematics and science teachers" (Messung professioneller Kompetenzen in mathematischen und naturwissenschaftlichen Lehramtsstudiengängen); MATE: Measure of Acceptance of the Theory of Evolution; MC: Multiple choice; MUM: Measure of Understanding of Macroevolution; ORI: Open Response Instrument; RaProEvo: Randomness and Probability Knowledge Test (context: Evolution).

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Authors' contributions

PK conducted the literature review in English language for the CINS, CANS, ACORNS, and MATE (1999 version), AM and TP conducted the literature review in English language for MUM, I-SEA, GAENE and MATE (2007 version). RP conducted the literature review in English language for the KEE and ATEEK. DC conducted the literature review in English language for GeDI and EM conducted the literature review in English language for the EvoDevoCI.

All authors conducted a literature review for all instruments in their spoken language(s), AB in German language. PK conducted the key word search in English language for all key words, all other authors conducted the key word search in their spoken language(s), AB in German language. PK compiled all data, conceptualized and wrote the manuscript. RP, AM and TP provided integrations to different sections of the draft, and RP contributed specific sections associated with the CINS instrument. All authors contributed to specific sections associated with literature they reviewed. AB supervised the project and contributed to the manuscript, especially concerning methodological issues. DG created Figs. 1 and 2. All authors discussed and revised the manuscript. All authors read and approved the final manuscript. This article was realized based on objectives of the COST Action 17127 collaboration and is part of research of Working Group 1 within the COST Action 17127. All authors read and approved the final manuscript.

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5 Paper II

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Development and evaluation of the knowledge about evolution 2.0 instrument (KAEVO 2.0)

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ABSTRACT

In evolution education, misconceptions about evolutionary concepts impact students' learning. Much research exists on assessing knowledge about evolution using different instruments. The current article introduces the KAEVO 2.0 instrument, which includes various evolutionary aspects representing microevolution and macroevolution. The introduced instrument aims to measure knowledge about evolution comprehensively, suitable for both high school students and undergraduates.

KAEVO 2.0 is based on KAEVO 1.0 (Beniermann, 2019) and was extended on the basis of a literature and a curricula analysis. These analyses revealed evolutionary concepts that reflect the construct 'knowledge about evolution' in high school biology. KAEVO 2.0 was reviewed by evolutionary biology and biology education experts and subsequently modified. Besides these aspects of content validity based on the content analyses, evidence for validity and reliability is provided based on a field-test with 136 biology, 124 non-biology undergraduates, and 146 high school students. We present confirmatory factor analyses (CFA), reliability analyses, correlation analyses and group comparisons for these subgroups. Results indicate that KAEVO 2.0 can be valuable in different application scenarios and is suitable for different age groups. We discuss further use of this instrument and recommend applications of various published instruments to assess different aspects of knowledge about evolution.

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Introduction

Evolution is one of the key concepts in biology and thus, of great importance regarding biology education. On the other hand, it has been repeatedly shown that many aspects of evolution are difficult to understand, such as the tremendous amount of time of Earth's history and the fact that evolution has no purpose or direction (Catley & Novick, 2009; Gregory, 2009; Trend, 2000; Trend, 2001). Reasons might be that many evolutionary concepts cannot be adequately understood with our everyday thinking. Several studies show that students tend to provide non-scientific explanations for the mechanisms of evolution (Bardapurkar, 2008; Fiedler et al., 2017; Nehm et al., 2012; Palmer, 1999). These

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'alternative conceptions' have an impact on students' learning and should, therefore, be understood as the basis for science teaching (Bishop & Anderson, 1990). Although these ideas are diverse and often resistant to instruction (Anderson et al., 2002; Ha et al., 2015; Kalinowski et al., 2016; Nehm & Reilly, 2007), conceptions on different aspects of evolution often do not differ arbitrarily between individuals (Gregory, 2009). Therefore, it is possible to cluster typical and recurring patterns and types of conceptions. This enables a systematic classification and description of common misconceptions of different evolutionary concepts.

To identify students' conceptions on evolution, mostly interviews or written tests with open or multiple choice response formats are used. Several instruments have been published to measure the knowledge concerning evolution by means of a questionnaire (e.g. *Evolution Concept Test* (ECT), Bishop & Anderson, 1990; *Concept Inventory of Natural Selection* (CINS), Anderson et al., 2002; *Concept Assessment of Natural Selection* (CANS), Kalinowski et al., 2016; *Measure of Understanding of Macroevolution* (MUM), Nadelson & Southerland, 2009; *Genetic Drift Inventory* (GeDI), Price et al., 2014; *Evo-Devo Concept Inventory* (EvoDevoCI), Perez et al., 2013), which differ in the examined evolutionary concepts and the target groups. Mead et al. (2019) reviewed a variety of these instruments from the last 25 years. All of the reviewed instruments focus on particular evolutionary concepts, for example on natural selection or genetic drift, and either on aspects of microevolution or macroevolution. Mead et al. (2019) emphasise the importance of applying measurement standards when developing instruments and demand evidence for reliability and validity of the respective instruments. Only if an instrument meets these criteria, can it be expected to provide consistent results when implemented in similar circumstances (American Educational Research Association [AERA], American Psychological Association, & National Council on Measurement in Education, 2014; Campbell & Nehm, 2013; Mead et al., 2019). Not all of the previously mentioned instruments meet all criteria of reliability and validity (Mead et al., 2019).

This article aims to introduce KAEVO 2.0, which contains aspects of evolution that high school students should know and combines microevolutionary and macroevolutionary concepts for measuring a huge variety of evolutionary concepts by use of one single instrument. This newly developed instrument is based on KAEVO 1.0 (Beniermann, 2019). KAEVO 1.0 includes multiple choice questions and was constructed to measure knowledge of various evolutionary concepts. In contrast to most existing instruments, KAEVO 1.0 consists of questions on several evolutionary concepts including both aspects of microevolution and macroevolution. However, in the development of KAEVO 1.0, only some aspects of validity were explicitly considered.

Thus, KAEVO 2.0 was extended and modified based on aspects of validity (AERA et al., 2014). To provide evidence for content validity and to ensure to cover all relevant aspects of evolution for a comprehensive overview of the construct 'knowledge about evolution', we first conducted a textbook and curricula analysis and identified the relevant evolutionary aspects. Second, European experts in the field of evolutionary biology and biology education reviewed all items. As a result of this further validation procedures, we extended the questionnaires by adding items on missing evolutionary aspects. Based on the expert review, we modified some items and deleted one item of the initial instrument.

The newly developed KAEVO 2.0 was utilised to assess evolutionary knowledge of high school and university undergraduate students. To address the issues of measurement standards in knowledge about evolution instruments, we report reliability and validity and discuss adequate application scenarios and suitability for different age groups.

Conceptions about different evolutionary concepts

There are several concepts for which a scientifically correct understanding is crucial for an overall understanding of evolution. The following widespread and recurring misconceptions have been discovered in studies around the globe (see detailed overviews in Gregory (2009); Harms and Reiss (2019)).

In terms of evolutionary adaptation and natural selection, *teleological* (Bardapurkar, 2008; González Galli & Meinardi, 2011; Gregory, 2009; Rosenberg & McShea, 2008; Sinatra et al., 2008), *anthropomorphic* (Fiedler et al., 2017; Gregory, 2009), *Lamarckian* (Crow, 2004; Gregory, 2009; Kampourakis & Zogza, 2006), *typological* (Alters, 2005; Gregory, 2009; Shtulman, 2006), and misconceptions about *automatic adaptation* (Brennecke, 2015; Evans, 2001) have been reported.

Besides these frequently occurring misconceptions, it is difficult for students to evaluate the *role of chance and probability* in evolution (Fiedler et al., 2017; Greene, 1990), to *read and interpret phylogenetic trees* (Phillips et al., 2012; Schramm et al., 2019), to describe and interpret the term *biological fitness* (Bishop & Anderson, 1986), and to understand the *dimensions of deep time* and to classify events in the history of the Earth (Catley & Novick, 2009; Libarkin et al., 2018).

Instruments measuring evolutionary concepts

Numerous studies deal with conceptions about evolutionary topics and processes. Recently, Mead et al. (2019) gave a detailed overview of many instruments of the past 25 years that are intended to measure the knowledge about evolution. Most of these instruments focus on natural selection (*Evolution Concept Test* (ECT), Bishop & Anderson, 1990; *Concept Inventory of Natural Selection* (CINS), Anderson et al., 2002; *Concept Assessment of Natural Selection* (CANS), Kalinowski et al., 2016) as the main mechanism of evolution. Further instruments aim to measure the knowledge about other evolutionary concepts like macroevolution (*Measure of Understanding of Macroevolution* (MUM); Nadelson & Southerland, 2009), genetic drift (*Genetic Drift Inventory* (GeDI); Price et al., 2014) or evolutionary developmental biology (*Evo-Devo Concept Inventory* (EvoDevoCl); Perez et al., 2013). KAEVO 1.0 (Knowledge About EVOlution; Beniermann, 2019) was developed to measure knowledge about several different evolutionary concepts and processes, including both microevolution and macroevolution. Detail information of all these instruments are summed up in Table 1.

For all instruments (except for reliability of the ECT), evidence for validity and reliability was provided in the original publications. Three instruments (CANS, CINS, and EvoDevoCI) consist of multiple choice questions only, one instrument (GeDI) includes only agree/disagree statements, and one instrument (ACORNS) is composed exclusively of open-ended questions. All other instruments consist of

Table 1. Summary of detail information of the instruments to assess knowledge about evolution (extended based on Mead et al., 2019). HS = High school students, UG = undergraduates, NM = non-majors, M = majors, T = teachers.

Instrument		ACORNS	CANS	CINS	ECT	EvoDevoCI	GeDI	KAEVO 1.0	KAEVO 2.0	MUM
Description		- Unlimited number of open-ended questions	- Twenty-four multiple choice questions	- Twenty multiple choice questions	- Two open-ended questions - Four items with a 5-point rating scale	- Eleven multiple choice questions	- Twenty-two agree/disagree statements	- Fourteen multiple choice questions - Eighteen true/false statements - Three timeline estimation items	- Fourteen multiple choice questions - Eighteen true/false statements - Three timeline estimation items	- Twenty-seven multiple choice questions - One open-ended question
Original population, country		UG, USA	UG-M, USA	UG-NM, USA	UG-NM, USA	UG-M, USA	UG-M, USA	HS (grade 7, 9, 10, and 11), UG, T, Germany	HS (grade 10, 11, and 12), UG-M, UG-NM, Germany	UG-M, USA
Intended populations (according to authors)	HS (grade 7-9)	- '[…] multiple versions of the instrument may be assembled to examine particular reasoning patterns […].' (Nehm et al., 2012, *p.* 93) - 'Such flexibility allows teachers to tailor the ACORNS to their own, unique curricula.' (Nehm et al., 2012, *p.* 93)		No recommendations given.	No recommendations given.			X		
	HS (grade 10 and higher)							X	X	
	NM		X[1]					X	X	X[2]
	M		X[3]			X	X	X	X	X[4]
	T							X	X	
Covered evolutionary concepts	Biological fitness			X[5]				X	X	
	Deep time							X	X	X
						X				

	Evolutionary developmental biology									
	Fossils									X
	Genetic drift						X			
	Heredity		X	X				X	X	
	Human evolution							X	X	
	Mutations		X						X	
	Natural selection	X	X	X	X			X	X	
	Non-adaptive Change	X								
	Phylogenetics								X	X
	Speciation			X				X	X	X
	Variation		X	X				X	X	
Reliability of the instrument		- Internal consistency - Inter-rater agreement	- Internal consistency - Stability	- Internal consistency	- Not available	- Internal consistency - Stability - Alternate forms	- Stability - Internal consistency	- Internal consistency	- Alternate forms - Internal consistency	- Internal consistency
Validity of the instrument		- Content - Substantive - External structure	- Content - Substantive	- Content - Substantive - Internal structure	- Content - Substantive	- Content - Substantive - External structure	- Content - Substantive - Generalisation	- Content - Substantive - Internal structure - External structure - Generalisation	- Content - Internal structure - External structure - Generalisation	- Content

[1]"The CANS […] was designed for estimating the ability of college students in introductory biology courses […]." (Kalinowski et al., 2016, p. 7)
[2]"[…] this instrument is designed to measure beginning college students' knowledge of macroevolution […]." (Nadelson & Southerland, 2009, p.176)
[3]"The CANS […] was designed for estimating the ability of college students in introductory biology courses […]." (Kalinowski et al., 2016, p. 7)
[4]"[…] this instrument is designed to measure beginning college students' knowledge of macroevolution […]." (Nadelson & Southerland, 2009, p.176)
[5]Covered evolutionary concepts differing from Mead et al. (2019).

multiple item types. Undergraduates are the original and also the intended population for most instruments (see Table 1). The intended target group for KAEVO 1.0 is high school students from grade 7 on, undergraduates (majors and non-majors), and teachers. All of these groups also served as original populations. Except for KAEVO 1.0 and MUM, all other instruments measuring knowledge about evolution focus on single microevolutionary concepts, most of them on natural selection (see Table 1).

Background of KAEVO

KAEVO in its original version (1.0; Beniermann, 2019) was developed as an instrument that should function as a tool for longitudinal studies, and it was initially utilised in German grade 7 up to a group of German biology teacher trainees (see Table 1). To enable insight into KAEVO 1.0, which was published in German, we will shortly introduce the items before we describe the validation process and present the modified and extended KAEVO 2.0.

KAEVO 1.0

KAEVO 1.0 was developed in an iterative process based on literature review, expert interviews, student interviews, expert reviews, student pre-tests, and a study with four different sampling groups (Beniermann, 2019). The items of KAEVO 1.0 were developed based on various other tests on knowledge about evolution (e.g. Bishop & Anderson, 1986; Brennecke, 2015; Graf, 2008; Jiménez-Aleixandre, 1992; Lammert, 2012). The foci of the development were on the one hand, on the respondent groups (their expected pre-knowledge and their language level) and on the other, on including different aspects of evolution in the questionnaire. This is based on the assumption that a broad and profound understanding of evolution involves more than solely knowledge about natural selection. An additional goal was to develop an instrument that is preferably short in handling time to be implemented in larger questionnaires without much effort. KAEVO 1.0 (Beniermann, 2019) is divided into three parts (A, B, and C). KAEVO-A contains nine multiple choice questions about *evolutionary adaptation and natural selection*, *biological fitness*, *speciation*, and *heredity of phenotype changes*. Five of these items are intended to test knowledge about *evolutionary adaptation and natural selection*. As previous studies revealed a context sensitivity in understanding natural selection (Brennecke, 2015; Nehm et al., 2012; Nehm & Ha, 2011; Palmer, 1996), different zoological and botanical examples were used. According to Nehm et al. (2012), another important context is familiarity. The contexts of two zoological (cheetahs, ducks) and one botanical item (cacti) were indicated as 'familiar,' while the other two contexts (banded snails, Venus flytraps) were specified as 'unfamiliar.' These items and their distractors were designed based on a qualitative interview study on high school students' preconceptions about evolutionary adaptation (Brennecke, 2015). The number of distractors (4-5) reflects the amount of relevant misconceptions in the respective contexts to take into account the quality requirement that a well-designed instrument should be able to detect as many misconceptions as possible (Kalinowski et al., 2016). The misconceptions can be divided into five categories: *automatic change*, *teleological with the nature as acting entity*, *teleological with the organism itself* *as acting entity*, *anthropomorphic* or *anthropomorphic and Lamarckian*. Anthropomorphic and Lamarckian represent the conception that the organism recognises the necessity to adapt and therefore adapts actively by means of training. This misconception was only suitable for items with zoological examples, since 'training' is rarely attributed to plants (Brennecke, 2015; Palmer, 1996).

The item used to assess knowledge about the concept of *biological fitness* is based on Bishop and Anderson (1986) and reassessed by means of student interviews. Two items focus on *heredity of phenotype changes* and are based on Jiménez-Aleixandre (1992) and extended based on student interviews. The question on *speciation* was developed based on student interviews. The answer option 'I don't know' is included in every item to avoid guessing when a student does not know the correct answer.

KAEVO-B contains six items with statements about evolutionary concepts like *speciation* or *human evolution* that have to be categorised as right or wrong and one multiple choice item on *human evolution*, which asks for the closest relative to chimpanzees and offers four answer options. All items offer the answer option 'I do not know.' The content of the items refers to common misconceptions and scientifically accurate statements about central evolutionary concepts.

KAEVO – C contains three items which focus on conceptions about deep time. They ask for the chronological classification of the existence of humans, dinosaurs, and the first living beings on a timeline that represents the history of the Earth ranging from 'origin of the Earth' to 'today.' To enable surveying of young Earth creationists, no dates are displayed on the timeline. Additionally, exact dates are not necessary for a scientifically correct understanding of deep time (Trend, 2001). Scales with absolute time can even harm the understanding of deep time (Trend, 2000), for instance because the learning of exact dates of events depends on the understanding of large numbers, which varies among learners (Cheek, 2012).

Objective of KAEVO 2.0

KAEVO 2.0 shall combine microevolutionary and macroevolutionary concepts to enable measuring a broad variety of evolutionary concepts with one single instrument. The instrument should contain all aspects of evolution that high school students should know. To refine KAEVO 2.0 based on KAEVO 1.0, we provide further sources of validity. First, a literature and curricula analysis provided grounds for the extension of the instrument. Second, experts in the field of biology and biology education reviewed this extended version of KAEVO 1.0. Third, based on the expert review, we modified some items and deleted one item, which resulted in KAEVO 2.0. Fourth, we tested KAEVO 2.0 in a pilot study on high school and university undergraduate students to provide further evidence for validity and reliability. By implementing new items about microevolution and macroevolution, KAEVO 2.0 is intended to enable diagnosing corresponding knowledge as differentiated as possible.

At the same time, the instrument was supposed to be 'easy-to-use,' as short as possible with closed answers that can be answered quickly. Additionally, we wanted the instrument to be suitable for different groups of participants in terms of previous knowledge and language level (starting from high school level). Therefore, KAEVO 2.0 was tested for high school students (grade 10, 11, and 12) as well as undergraduates (biology majors and non-majors).

Summed up, it can be stated that KAEVO 2.0 is intended to be an 'allrounder' among the instruments that seek to measure knowledge about evolution, whereas all commonly used instruments are rather 'specialists', being helpful for measuring special target groups or special evolutionary concepts, especially natural selection.

Methods

Content analyses

Analyses of two German school curricula as well as of internationally distributed and common textbooks were performed ('Evolution,' Futuyma, 2013; 'Campbell Biology,' Urry et al., 2017). According to the textbook analysis, many fundamental aspects of evolution were already included in KAEVO 1.0, such as *biological fitness*, *evolutionary adaptation and natural selection*, *heredity*, *speciation*, *human evolution*, and *deep time* (Futuyma, 2013; Urry et al., 2017). However, some relevant aspects were missing, like *tree reading*, *variation as necessary for speciation*, and *genetic drift*.

We intended our instrument to not only be utilisable for measuring knowledge about evolution of university students, but also of high school students. Thus, we analysed two school curricula of the German state Hesse exemplarily. The school curricula for grade 5–10 and for upper secondary education were analysed. The curriculum for grade 5–10 is divided into different basic concepts. One of these basic concepts is *development*, which includes *reproduction* and *individual development* on the one hand and *evolutionary processes* on the other hand (Hessisches Kultusministerium [HKM], 2011). Within this concept, it is determined which aspects of evolution should be known after finishing grade 6 and 10. After finishing grade 6, students should have learned about *phenotype changes* (e.g. because of muscle training) and the connection between the *morphology*, *lifestyle*, and the *habitat of species*. After finishing grade 10, the aspects *heredity*, *variation*, *deep time*, *human evolution*, *phylogenetic trees*, *mutations*, and *natural selection* should have been taught in biology lessons (HKM, 2011).

In upper secondary education, students can choose between attending a basic or advanced course in biology. The curriculum for upper secondary education is also divided into different basic concepts. The basic concepts *reproduction*, *variability and adaptation*, and *history and relationship* contain evolutionary processes. Evolution is a topic for one school semester in upper secondary education and includes the aspects *natural selection*, *variation*, *mutations*, *speciation*, and *human evolution*. For students attending an advanced course, the semester also includes *population genetics*, *genetic drift*, and *co-evolution* (HKM, 2016).

The concepts that turned out to be relevant in both the textbooks and the school curricula were included in KAEVO 2.0. The concepts *population genetics* and *genetic drift* are only mandatory for students attending advanced biology courses in upper secondary education (HKM, 2016), so that they have been neglected in KAEVO 2.0 to enable surveys in high schools. KAEVO 2.0 shall be ready-to-use in grade 10 based on the curricula analyses.

On the basis of our reviews the following evolutionary concepts were added to KAEVO 2.0: *tree reading*, *variation as necessary for speciation*, and *mutations*.

Development of the additional items

Two items dealing with phylogenetic trees have been developed (A9.1 and A9.2) to assess respondents' *tree reading* comprehension. A diagonal format (ladder format) with a horizontal reading direction was used with four fictional species (A-, B-, C – and D-squirrels). Even though the ladder format is hard to understand compared to other representations (Novick & Catley, 2007), it is widespread in text-books from USA (Catley & Novick, 2009) and other countries. An own textbook analysis also revealed the frequent use of the ladder format. Therefore, we chose the most common format for learners. The horizontal reading direction allows respondents to read the tree more easily, as it follows the order of reading text (Novick et al., 2012). Fictional species were used to avoid overlaying knowledge. The first item (A9.1) asks for the direction of the time arrow. The answer options correspond to the eight main directions of a compass rose (e.g. north, north-east, east, etc.). The respondents should select the arrow that represents the correct timeline (east).

The second item (A9.2) asks about the kinship between the different squirrel species. Different answer options about the relationship of C-squirrels to the other squirrel species are provided, which include common misconceptions about evolutionary trees. For instance, answer option 5 represents the misconception that species drawn closer together are more closely related to each other than those placed farther apart (Meir et al., 2007). The answer option '*… as closely related to A as to B as to D-squirrels*' represents the common misconception that the number of nodes crossed in tracing a path between two species on a phylogenetic tree is an indicator for how closely related they are (Meir et al., 2007).

Item A10 was developed to address *speciation including variation* as an important evolutionary concept and therefore as an addition to the speciation item (A4) of the initial instrument. The new item asks for the most likely long-term development after an ice age. Six different answer options are offered that show rabbit populations at different points in time with a focus on their fur colour. According to the requirements of Fischer (2015) for items to assess knowledge about variation, this item only asks students about variation within a rabbit population over time and not how they adapted. Answer options include the scientific view, common misconceptions or allow for an individual answer of the respondents. All displayed misconceptions can be classified as typological.

Furthermore, eleven items (B7.1 – B7.11) were developed to assess conceptions about *mutations*, divided into the subscales *conditions leading to mutations* (B7.6, B7.7, B7.10, and B7.11), *randomness of mutations* (B7.1, B7.2, and B7.4), and *effects of mutations* (B7.3, B7.5, B7.8, and B7.9). The items are statements that have to be rated as true or false. This answer format was chosen to enable the incorporation of a larger number of items with a variety of different aspects and misconceptions about mutations. On the downside, the true-false format cannot be used to investigate in detail which alternative ideas students have. On the upside, students are asked to choose one answer option in the true-false format, since they often have both scientifically accurate conceptions and misconceptions about evolutionary concepts (Andrews et al., 2012; Nehm & Schonfeld, 2008) and therefore consider more than one answer option in multiple choice tests (Parker et al., 2012). Additionally, such a format offers the opportunity to address many different aspects of an evolutionary concept and to keep the instrument as short as possible at the same time.

Review process

A group of European experts in evolutionary biology and biology education was part of the developing and validation process. To enable the use of KAEVO 2.0 in an international context, we translated the instrument into English and retranslated it with the support of native speakers and experts in the field of biology education. Subsequently, European experts in the field of evolutionary biology and biology education reviewed KAEVO 1.0 including the additional items that resulted from the content analyses. The expert board consisted of working group members of a European research network on understanding evolution. As a result of this further content validation, five items have been modified and item A9 of KAEVO 1.0 has been excluded (see Appendix, Table 11). The resulting version of KAEVO 2.0 was then field tested and subjected to several validity and reliability analyses.

Sources of evidence for reliability and validity

To ensure an appropriate internal structure and test for dimensionality, a CFA was conducted for all evolutionary concepts that are represented by more than one item in KAEVO 2.0 instrument based on the entire sample. To provide evidence for validity by means of external structure, the ATEVO (Beniermann, 2019) was used for correlational analysis. The ATEVO was developed to assess if and to what extent people agree with evolution as a fact and therefore the common descent of all living beings and change of species over time. The external structure of an instrument can be indicated as valid if the construct fits to expected external models (Mead et al., 2019). Beniermann (2019) conducted a correlational analysis of KAEVO-A 1.0 with ATEVO and found a moderate positive correlation between attitudes and knowledge about evolution. This relationship increased with age and education level.

KAEVO 1.0 was reported to be suitable for different age and educational levels (Beniermann, 2019). To test if the extended and modified KAEVO 2.0 is meaningful across different populations, two different survey populations and age groups were tested. To test the internal consistency of KAEVO 2.0 reliability analyses were conducted (Cronbach's α and Spearman-Brown coefficient (split-half reliability)). The internal consistency of an instrument can be described as appropriate at a Cronbach's α of at least 0.7 (Field, 2013; Schmitt, 1996) (see Cronbach's α of KAEVO 2.0 in Table 6). Cronbach's α increases with the number of items on an instrument. Thus, an instrument with Cronbach's α below 0.7 can also be reliable, if it contains only few items (Field, 2013).

Survey population

406 respondents voluntarily participated in the study. Participants belong to three separate subgroups (Table 2) to enable a statement about usability generalisation of KAEVO 2.0 in samples with varying prior knowledge and different age. All subgroups received the same instructions, which included giving only one answer per question, reading all

Table 2. Sample sizes of the subgroups. (a) biology undergraduate students, (b) non-biology (English language and literature, and mathematics) undergraduate students, and (c) high school students.

		Age (years)		Sex (%)	
Subgroups	N	Ø	Range	Female	Male
(a)	136	20.4	17–31	58.8	40.4
(b)	124	21.3	18–37	55.6	41.9
(c)	146	17.0	15–19	58.9	41.1
total	406	19.4	15–37	57.9	41.1

instructions carefully, answering from a biologist's perspective in the knowledge parts, not guessing or looking up, and choosing 'I don't know' if appropriate. Incompletely answered parts were excluded.

Analyses

All KAEVO 2.0 item answers were dichotomised prior to the analyses (correct = 1; wrong/not known = 0) in order to form sum values. Hence, a higher score represents a better knowledge of the respective evolutionary concepts. To compare the three subgroups, one-way analyses of variance (ANOVA) were performed. Scheffé tests were carried out as a post-hoc procedure. The differences were defined as significant at a level of $p < 0.01$.

Heat maps were used to illustrate the results of the *deep time* tasks (C1 and C2). The frequencies of the data for each millimetre of the time axis are reflected by the colours in the heat map. The heat maps thus illustrate the ideas about the existence of dinosaurs and humans in a colour gradient. Additionally, the whole timeline was divided in 29 sections with 9 mm length each. One section reflects about 158.6 million years.

Results

On average, biology undergraduate students reached the highest scores, high school students the lowest scores for the entire KAEVO 2.0 instrument, as well as in all single parts (see Table 3).

The means of the sum score of all KAEVO 2.0 items between the three subgroups showed a significant difference ($F[2,329] = 17.901$, $p < 0.01$). Biology undergraduates had the highest average knowledge and differed significantly from high school students who answered least questions correctly. The effect size of group membership on the knowledge of evolution was moderate ($\eta^2 = 0.098$).

Table 3. Scores of KAEVO-A, -B 2.0, and total per subgroup. (a) biology undergraduate students, (b) non-biology (English language and literature, and mathematics) undergraduate students, and (c) high school students. KAEVO-A 2.0: possible scores between 0 (no question answered correctly) and 12 (all questions answered correctly). KAEVO-B 2.0: Possible scores between 0 and 17. KAEVO 2.0 total: Possible scores between 0 and 29.

	N			*M*			*SD*		
	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
KAEVO-A 2.0	117	115	130	4.85	4.31	3.39	2.14	2.43	2.00
KAEVO-B 2.0	123	117	127	12.85	11.84	11.13	2.14	2.81	2.96
KAEVO 2.0 total	108	109	115	17.99	16.23	14.71	3.57	4.43	4.21

Table 4. Item difficulty per item of KAEVO 2.0 per subgroup. (a) biology undergraduate students, (b) non-biology undergraduate students, and (c) high school students. Difficulty = percentage of students choosing the correct answer for a particular item.

		N			*Item difficulty*		
		(a)	(b)	(c)	(a)	(b)	(c)
A1	Evolutionary adaptation of Venus flytraps	135	123	146	62.2	39.0	28.8
A2	Biological fitness	136	124	144	25.7	18.5	6.9
A3	Evolutionary adaptation of cheetahs	136	124	146	72.1	55.6	38.4
A4	Speciation	136	123	145	13.2	22.0	15.9
A5	Evolutionary adaptation of snails	133	123	145	72.9	60.2	41.4
A6	Evolutionary adaptation of cacti	134	123	145	59.7	49.6	28.3
A7	Heredity of phenotype changes I	135	124	146	90.4	82.3	84.9
A8	Heredity of phenotype changes II	135	124	144	44.4	41.1	50.7
A9.1	Tree reading I	131	121	141	13.0	19.8	5.7
A9.2	Tree reading II	125	122	140	3.2	10.7	6.4
A10	Speciation including variation	130	121	143	69.2	62.8	50.3
A11	Human evolution (relatives of chimpanzees)	132	122	143	28.0	23.8	35.0
B1	Adaptation of a single individual	135	122	144	47.4	50.0	48.6
B2	Evolution leads to improvement	136	123	144	72.1	74.0	68.8
B3	Ancestor of humans and chimpanzees	134	122	144	70.9	67.2	53.5
B4	Better adaptation means higher probability of more offspring	135	123	145	91.9	94.3	84.1
B5	No speciation without differences	133	123	142	66.2	51.2	52.1
B6	Evolution of mankind is completed	136	123	145	90.4	88.6	73.8
B7.1	Mutations happen randomly	133	121	146	91.0	78.5	72.6
B7.2	Mutations controlled by organism	136	123	146	94.1	83.7	87.0
B7.3	Mutations are always negative	134	121	144	97.0	90.1	92.4
B7.4	Mutations more frequently after environmental changes	136	122	143	16.9	12.3	14.0
B7.5	Mutation effects can be neutral	136	122	144	84.6	70.5	70.1
B7.5	Mutations are triggered only by radiation	136	123	145	86.8	86.2	80.0
B7.7	Mutation normally don't occur in living beings.	135	123	145	91.1	87.8	70.3
B7.8	Mutations are fundamental to evolutionary change	134	123	146	85.8	71.5	67.8
B7.9	Mutation body (somatic) cells no effect on evolution	134	122	143	14.2	9.0	11.2
B7.10	Mutations take place on a regular basis	133	123	146	84.2	77.2	74.7
B7.11	Mutations independent of environmental changes	134	123	146	87.3	87.0	80.8

In part A, the most difficult items were the items on *biological fitness* (A2), one of the *speciation* items (A4), and *tree reading* (A9.1 and 9.2). The items on *heredity* (A7 and A8) were solved correctly the most often. Difficulty of item A8 on *heredity of phenotype changes* was more challenging than item A7, which covers a similar content in an extended period (Table 4).

In part B, the items on mutations (B7.1–7.11) showed low item difficulty except for item B7.4 ('*mutations happen more frequently after environmental changes*') and item B7.9 ('*mutations of body (somatic) cells have no effect on evolution*'), which showed high item difficulties. Additionally, items B4 ('*better adaptation means a higher probability of more offspring*') and B6 ('*the evolution of mankind is completed*') were solved correctly on average by 84.1–94.3% (B4) and 73.8–90.4% (B6) of the students, which indicates a low item difficulty.

Items on evolutionary adaptation and natural selection

The items on *evolutionary adaptation and natural selection* showed similar distributions of misconceptions among the three subgroups (Figure 1). The items dealing with zoological species possessed lower item difficulties than the items containing botanical examples. Students in all subgroups indicated 'I do not know' predominantly in

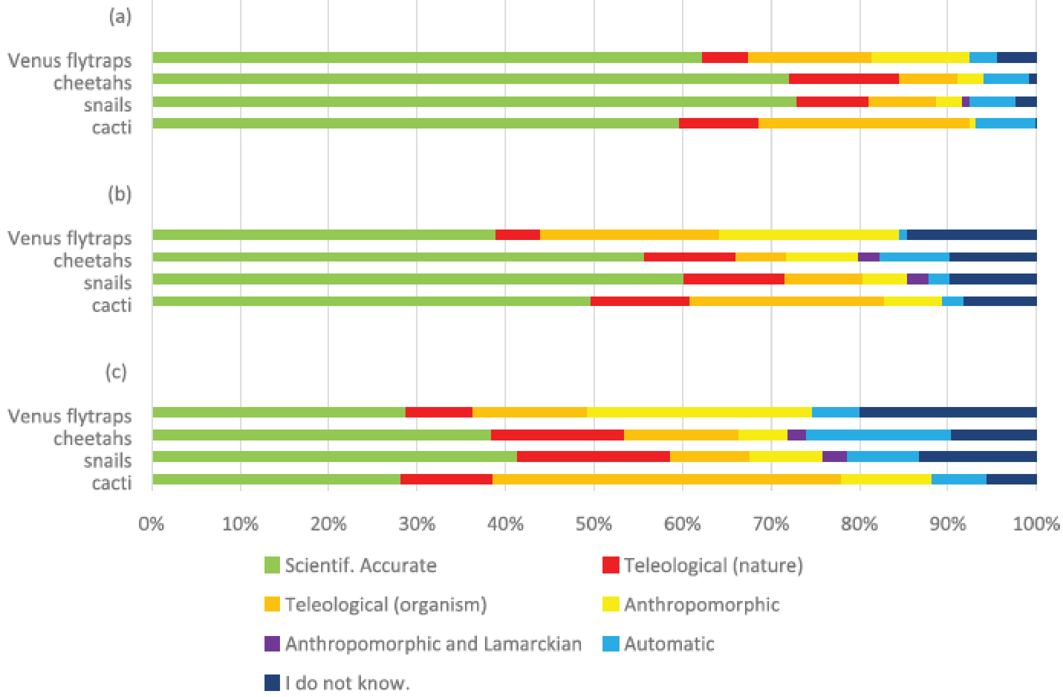

Figure 1. Percentage of the correct answers of the items on evolutionary adaptation per subgroup. (a) biology undergraduate students (Venus flytraps: N = 135; cheetahs: N = 136; snails: N = 133; cacti: N = 134), (b) non-biology undergraduate students (Venus flytraps: N = 123; cheetahs: N = 124; snails: N = 123; cacti: N = 123), and (c) high school students (Venus flytraps: N = 146; cheetahs: N = 146; snails: N = 145; cacti: N = 145). The answer option 'Anthropomorphic and Lamarckian' was only given in the zoological items.

unfamiliar contexts (banded snails, Venus flytraps). The misconceptions of all subgroups were dominated by teleological conceptions. Among all subgroups, anthropomorphic misconceptions occurred the most frequent in the item about Venus flytraps. Overall, the Lamarckian misconception was very rare, as well as the misconception that changes occur 'automatically.'

New items in KAEVO 2.0

The students' misconceptions were similarly distributed between the subgroup in the items on *tree reading* (A9.1 and A9.2). Many students in all subgroups did not know the correct answer of both items and therefore indicated 'I do not know.' (40.5% (A9.1) and 36.0% (A9.2) biology undergraduates, 35.5% (A9.1) and 28.7% (A9.2) non-biology undergraduates, 51.8% (A9.1) and 35.7% (A9.2) high school students; see Table 4). In A9.1, the dominating misconceptions in all subgroups were that the real timeline follows the 'main branch,' from the lower left to the upper right corner or the other way around. In A9.2, the common misconception that species drawn closer together are more closely related to each other than those placed farther apart was one of the two dominating misconceptions (20.8% biology undergraduates, 22.1% non-biology undergraduates, 24.3% high school students). Also, in all subgroups, many students thought that C-squirrels are most closely related to A-squirrels (18.6% biology undergraduates, 18.9% non-biology undergraduates, 20.8% high school students).

The most frequently chosen distractors of item A10 on *speciation including variation* were that all individuals of a population get lighter fur over time until all individuals are white (10.0% biology undergraduates, 9.9% non-biology undergraduates, 18.9% high school students) and that the number of individuals with white fur increases over time until the whole population has white fur (16.9% biology undergraduates, 21.5% non-biology undergraduates, 20.3% high school students).

KAEVO-C

None of high school students, 2.4% of biology undergraduates, and 2.6% of non-biology undergraduates located the phase of existence of humans on Earth scientifically accurate. However, 15.3% of high school students, 27.6% of non-biology undergraduates, and 34.4% of biology undergraduates located the origin of humans within the last section of the timeline (reflecting 158.6 million years; see Figure 2). 5.6% of biology undergraduates, 12.1% of non-biology undergraduates, and 17.5% of high school students located the origin of humans on Earth in the first third of the history of Earth (reflecting about 1.59 billion years).

Overall, five of 406 students (one biology undergraduate, four non-biology undergraduates) located the origin of dinosaurs on Earth in a scientifically accurate way (247 mm +/- 2 mm), while five students (three biology undergraduates, one non-biology undergraduate, and one high school student) were able to indicate the extinction of dinosaurs correctly (256 mm +/- 2 mm). 48.3% of non-biology undergraduates, 52.0% of biology undergraduates, and 70.4% of high school students located the origin of dinosaurs on Earth in the first third of the history of earth (Figure 2). 87.1% of non-biology undergraduates, and in each case 91.9% of high school students and biology undergraduates indicated the extinction of dinosaurs before their actual origin in the history of the Earth.

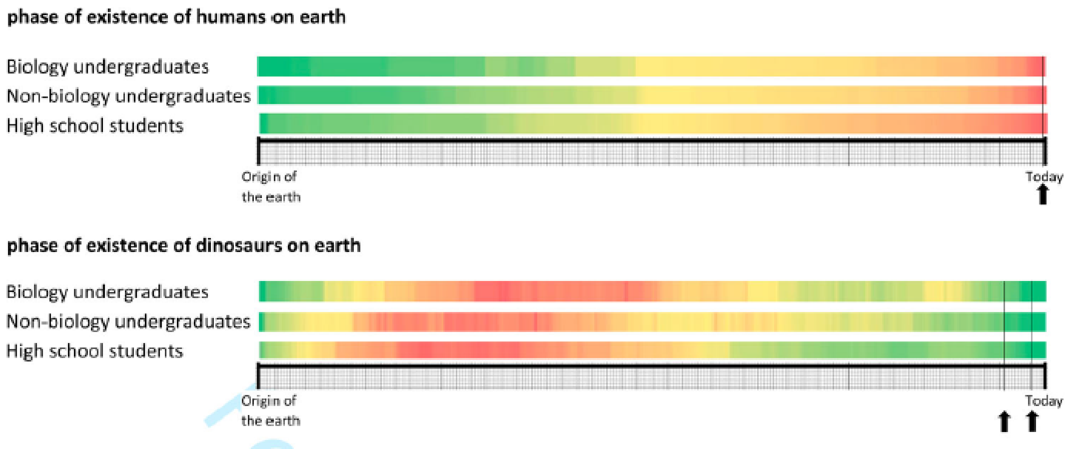

Figure 2. Classifications per subgroup. Heatmap ranging from green (no answers in this sections) to red (most amount of answers in this sections). The scientifically accurate classification is indicated by the black arrows (existence of humans: 25.9 cm (200.000 years ago) – today; existence of dinosaurs: 24.7 cm (235 m years ago) – 25.6 cm (65 m years ago)). Biology undergraduate students: N = 125 (humans), N = 123 (dinosaurs); non-biology undergraduate students: N = 116 (humans and dinosaurs); high school students: N = 137 (humans), N = 135 (dinosaurs).

Table 5. Means in mm of indicated points in time for the origin of humans and the phase of existence of dinosaurs on Earth per subgroup.

	Origin of humans on Earth	Origin of dinosaurs on Earth	Extinction of dinosaurs on Earth
Scientifically accurate	259	247	256
Biology undergraduates	212	107	152
Non-biology undergraduates	204	111	161
High school students	174	70	129

On average, undergraduate students indicated both the phase of existence of humans and dinosaurs on Earth in a more scientifically accurate way than high school students (Table 5). Biology undergraduates were scientifically more accurate than non-biology undergraduates regarding the origin of humans on Earth, but less scientifically accurate regarding the phase of existence of dinosaurs on Earth.

76.6% of all participants indicated a point in time for the origin of life before the scientifically accurate view. Less than 5% of the students among all subgroups indicated a scientifically accurate point in time (within section 9).

Internal structure of KAEVO 2.0

The goal of testing the internal structure is to demonstrate that the items of an instrument are related to each other as intended. It can be estimated that items that correlate strongly with each other measure the same aspect (Campbell & Nehm, 2013). The KAEVO is designed to measure different evolutionary aspects, which should be reflected as separated dimensions in the dimensionality.

CFA were conducted for all concepts that are represented by more than one item of KAEVO-A and -B. For KAEVO-A, these concepts are *evolutionary adaptation and natural selection* (items A1, A3, A5, and A6), *heredity of phenotype changes* (A7 and A8), *tree reading* (A9.1 and A9.2), and *speciation including variation* (A4 and A10). This four-dimensional model was tested for the whole sample as well as separately for high school students and undergraduates. The CFA of the whole sample for this predicted four-dimensional model showed a good model fit (CMIN/DF = 1.816; CFI = 0.966; RMSEA = 0.048, PCLOSE = 0.542) (see Figure 3).

CFA of the subgroups also showed a good model fit (high school students: CMIN/DF = 1.714; CFI = 0.916; RMSEA = 0.075, PCLOSE = 0.119; undergraduates: CMIND/DF = 1.385; CFI = 0.972; RMSEA = 0.041, PCLOSE = 0.671) and confirmed the four-dimensional structure.

Another CFA was conducted for all items on knowledge about mutations in KAEVO-B that are theoretically assumed to reflect the three subscales *conditions leading to mutations* (B7.6, B7.7, B7.10, and B7.11), *randomness of mutations* (B7.1, B7.2, and B7.4), and *effects of mutations* (B7.3, B7.5, B7.8, and B7.9). The initial three-dimensional solution including all eleven items showed a poor model fit. Items with highest item difficulties (B7.4 and B7.9) showed the lowest regression weights in the model and were subsequently removed. Item B7.8 was identified as potentially ambiguous and was consequently removed.

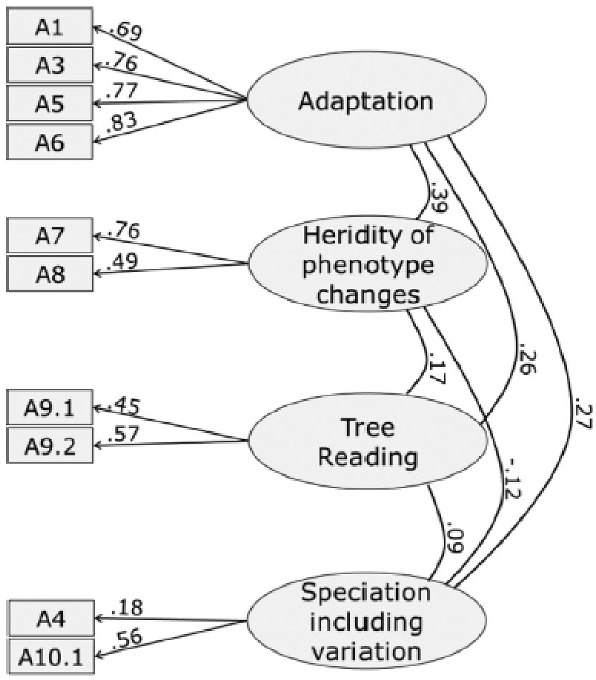

Figure 3. Confirmatory factor analysis of the KAEVO-A items. Method of estimation: Maximum Likelihood. Standardised regression weights are displayed on the arrows. Error terms not displayed.

Based on the remaining eight items, the assumed three-dimensional model was confirmed. The CFA of this three-dimensional model showed a good model fit (CMIN/DF = 2.508; CFI = 0.934; RMSEA = 0.064, PCLOSE = 0.159) (see Figure 4).

However, the model fit could be improved by exclusion of items B7.6 and B7.10 that showed lowest regression weights in this model (CMIN/DF = 2.266; CFI = 0.976; RMSEA = 0.058, PCLOSE = 0.318). This leads to a three-dimensional solution with two items per dimension as final model (see Figure 4).

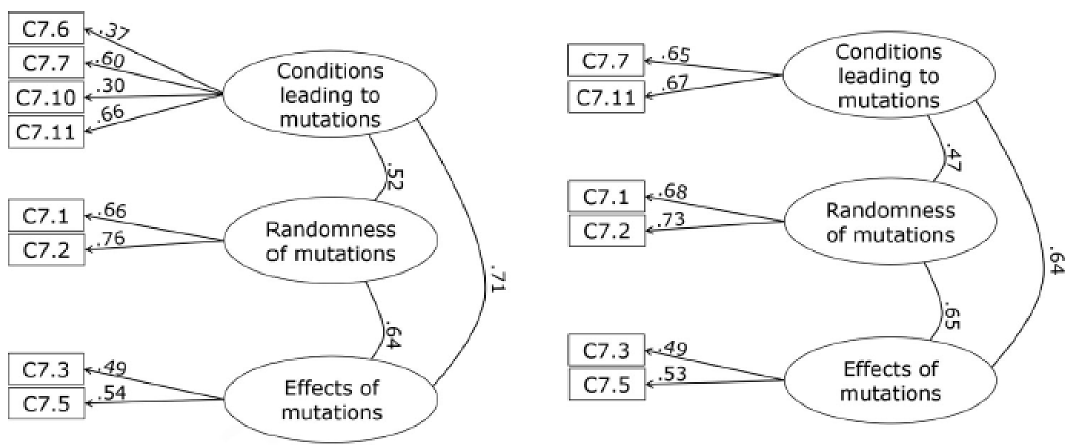

Figure 4. Confirmatory factor analyses of the mutation items. Solution with eight items on the left side, final solution with six items on the right side. Method of estimation: Maximum Likelihood. Standardised regression weights are displayed on the arrows. Error terms not displayed.

Table 6. Reliability (Cronbach's alpha and Spearman-Brown split-half reliabiliy) of the adaptation and mutation items of KAEVO 2.0. α = Cronbach's alpha; r = Spearman-Brown split-half reliability.

	Mutation items			Adaptation items		
Subgroups	*α*	*r*	*N*	*α*	*r*	*N*
High school students	0.730	0.786	141	0.822	0.855	145
Non-biology undergraduates	0.781	0.807	119	0.860	0.864	122
Biology undergraduates	0.675	0.806	128	0.813	0.824	131
total	0.751	0.803	388	0.851	0.865	398

The CFA of high school students also showed a good model fit (CMIN/DF = 1.913; CFI = 0.958; RMSEA = 0.083, PCLOSE = 0.194), while a CFA of the subgroups of undergraduates could not be performed due to a too small sample size.

To test reliability of scales, Cronbach's alpha should be used separately to items that relate to different aspects (Field, 2013). Therefore, the four *evolutionary adaption and natural selection* items of KAEVO-A and all *mutation* items were tested for internal consistency. The *evolutionary adaptation and natural selection* items showed a good reliability for the whole sample as well as for the subgroups. Reliability of the six *mutation* items of the final model was tested for all six items together, since the factors are highly correlated. The *mutation* items showed a good reliability for the whole sample and good or acceptable reliability for the individual subgroups (see Table 6).

Discussion

KAEVO 2.0 was developed to assess knowledge of several microevolutionary and macroevolutionary concepts in populations that differ in age (high school from grade 10 on and undergraduate students) and educational level (high school students, biology, and non-biology undergraduates). Based on the present data, we provided sources of evidence, indicating that the measured variables represent knowledge about evolution appropriately and that KAEVO 2.0 provides consistent results in comparable contexts.

Evidence for validity and reliability of KAEVO

Mead et al. (2019) emphasised the importance of systematic evaluation of instruments during their development in order to meet the quality control standards established by for instance the American Educational Research Association (AERA et al., 2014).

Based on Mead et al. (2019), we summarised the multiple forms of evidence for validity (Table 7) and reliability (Table 9) that were used as sources for the development of KAEVO 2.0.

Former results based on KAEVO 1.0 showed that knowledge about evolution across the different samples increased with age and education level, as expected. A strong effect was found, which was significant across all subgroups (Beniermann, 2019). The comparable sample groups surveyed with KAEVO 2.0 in the present study showed the same differences. Knowledge about evolution also increased with age and education level for the whole KAEVO 2.0 as well as for all separate parts. The moderate effect size of group membership for the whole KAEVO 2.0 was significant between high school and undergraduate students.

Table 7. Sources of evidence for validity. Overview based on Mead et al. (2019).

source	description	methodology	referring to instrument	*N*	results	references
content	assessment represents knowledge domain	1. **literature review** of instruments to assess understanding of evolution or single evolutionary concepts	KAEVO 1.0	-	Theory-based selection of items for initial item pool	Beniermann, 2019
		2. **text book/curricula review**	KAEVO 2.0	-	Theory-based selection of relevant evolutionary concepts	present study
		3. **target group survey** for construction of distractors (a) interview survey with university students based on newly created and published items	KAEVO 1.0	*11*	Formulation of distractors based on qualitative content analysis	Beniermann, 2019
		3. **target group survey** for construction of distractors (b) interview survey with high school students based on newly created items	adaptation items of KAEVO 1.0	*18*	Formulation of distractors based on qualitative content analysis	Brennecke, 2015
		4. **expert ratings of test items** review of items via experts of the field of biology education and evolutionary biology	(I) KAEVO 1.0 (II) KAEVO 2.0	*(I) 6* *(II) 13*	Selected items represent the theoretical constructs	(I) Beniermann, 2019 (II) present study
substantive	thinking processes used to answer are as intended	**Pre-Test** with younger learners (grade 7–12), focus on reasons of answer selection and comprehensibility	KAEVO 1.0	*142*	No barriers to content-related answering processes identified	Beniermann, 2019
internal structure	items capture intended construct structure	**Principal Component Analysis** to identify the dimensionality	(I) adaptation items of KAEVO 1.0	*(I) 1056*	(I) unidimensional structure representing one construct in accordance with theoretical assumptions	(I) Beniermann, 2019
		Confirmatory Factor Analyses to confirm the dimensionality	(I) all multiple-choice items of KAEVO 2.0 (II) Mutation	*(I) 398* *(II) 388*	(I) four-dimensional structure in accordance with theoretical assumptions that knowledge about evolution is represented by several constructs	(I) present study (II) present study

			items of KAEVO 2.0		(II) three-dimensional structure in accordance with theoretical assumptions	
external structure	construct aligns with expected external patterns	**Correlational analyses** with acceptance of evolution (a) For KAEVO-A 1.0 (b) For KAEVO-A 2.0	(I) KAEVO 1.0 (II) KAEVO 2.0	*(I) 974* *(II) 316*	(I) moderate correlation between the two instruments ($r = .33^{**}$; $p < 0{,}001$) (II) weak correlation between the two instruments ($r = .299^{*}$ $p < 0{,}001$)	(I) Beniermann, 2019 (II) present study
generalisation	scores meaningful across populations and contexts	**Comparison across contextual diversity** (a) tested for four different age groups (KAEVO 1.0) (b) tested for two different age groups (KAEVO 2.0)	(I) KAEVO 1.0 (II) KAEVO 2.0	*(I) 1056 (202 (grade 7), 224 (grade 9-11), 535 (university students), 95 (biology teacher trainees))* *(II) 406 (134 high school students, 144 undergraduates)*	- Differences in knowledge between groups as expected - Comparable reliability - Higher correlation between acceptance and knowledge for samples with more elaborated knowledge as expected	(I) Beniermann, 2019 (II) Present study

A CFA of the multiple choice items of KAEVO-A indicated evidence for an internal structure that is concordant with theoretical assumptions, as the predicted four-dimensional structure showed a good model fit for the whole sample as well as for the subgroups. The extracted factors represent four distinct concepts of evolutionary knowledge (*evolutionary adaptation and natural selection*, *heredity of phenotype changes*, *tree reading*, and *speciation including variation*). Two additional theoretically assumed constructs (*biological fitness* and *human* evolution) are only represented by one item each and could therefore not be included in the CFA. Thus, no evidence for validity in terms of dimensionality could be provided for these two items. Based on our text-book and curricula analyses as well as the expert review, we recommend to leave these two items in the instrument, as they showed evidence for content validity.

A CFA of the *mutation* items also indicated evidence for an internal structure concordant with theoretical assumptions after excluding ambiguous items as well as items with small regression weights. The resulting three-dimensional model includes six items and should be implemented in this form in further studies to avoid ambiguity within items.

To test the external structure of KAEVO 2.0, we performed a correlation analysis between KAEVO-A 2.0 and both ATEVO and its two subscales (see Table 8). The samples of biology and non-biology undergraduates surveyed with KAEVO 2.0 were pooled to get comparable groups to the undergraduates surveyed with KAEVO 1.0 (grade 7 school students, grade 9–11 school students, undergraduate students of different fields, and future teachers with the subject biology) in the reference study [Beniermann, 2019]. We found a positive significant correlation with weak effect size between knowledge about evolution and attitudes towards evolution for the surveyed high school students. Previous studies showed various results. No significant correlation between knowledge and attitudes was found for German grade 5–6 school students (Fenner, 2013), while grade 9–10 high school students in Germany showed a weak positive correlation (Lammert, 2012). The results for KAEVO-A 1.0 also varied, as no significant correlation was found for grade 7 school students, but a weak positive correlation was found for grade 9–11 high school students, which is in concordance with our results for grade 10–12 high school students [Beniermann, 2019]. However, we found a positive significant correlation with weak effect size between knowledge about and attitudes towards evolution for the undergraduate students. This is in accordance with previous studies (Akyol et al., 2012; Athanasiou, Katakos, & Papadopoulou, 2016; Graf & Soran, 2010; Deniz & Sahin, 2016; Großschedl et al., 2014; Großschedl et al., 2018; Nehm et al., 2013) comparable with the results for KAEVO-A 1.0 [Beniermann, 2019].

Table 8. Correlations of KAEVO-A 1.0 and 2.0 with ATEVO, ATEVO-EG, and ATEVO-EM scores of the sub-groups. (a) high school students (grade 7), (b) high school students (grade 9–12), (c) undergraduate students, and (d) future biology teachers. ATEVO-EG = subscale Evolution Generally; ATEVO-EM = subscale Evolution of the human Mind. *Correlation is significant at the $p < 0.01$ level.

	KAEVO-A 1.0*				KAEVO-A 2.0*			
	N	ATEVO	ATEVO-EG	ATEVO-EM	N	ATEVO	ATEVO-EG	ATEVO-EM
(a)	180–186	0.060	0.026	0.078	-	-	-	-
(b)	202–206	0.222*	0.213*	0.175*	108–110	0.255*	0.272*	0.160
(c)	502–507	0.295*	0.284*	0.253*	202–206	0.268*	0.293*	0.186*
(d)	90–92	0.449*	0.344*	0.408*	-	-	-	-
total	974–990	0.327*	0.291*	0.286*	310–316	0.299*	0.316*	0.202*

Table 9. Sources of evidence for reliability. Overview based on Mead et al. (2019).

source	description	methodology	referring to instrument	*N*	results	references
stability	scores consistent from one administration to another	not performed	-	-	-	-
alternate forms	scores comparable when using similar items	Spearman-Brown double length formula: split half. (a) for items that account for the same latent construct	(I) adaptation items of KAEVO 2.0 (II) mutation items of KAEVO 2.0	398	(I) Good reliability for adaptation items of KAEVO 2.0 $r = 0,865$ (II) Good reliability for mutation items of KAEVO 2.0 $r = 0,803$	present study
		Spearman-Brown double length formula: split half. (b) tested for three different age/education groups (KAEVO 2.0)	(I) adaptation items of KAEVO 2.0 (II) mutation items of KAEVO 2.0	*(Ia) 145 (high school students)* *(Ib) 122 (undergraduates non-biology)* *(Ic) 131 (undergraduates biology)* *(IIa) 145 (high school students)* *(IIb) 122 (undergraduates non-biology)* *(IIc) 131 (undergraduates biology)*	Good reliability for (Ia) $r = 0,855$ (Ib) $r = 0,864$ (Ic) $r = 0,824$ Good reliability for (IIa) $r = 0,786$ (IIb) $r = 0,807$ (IIc) $r = 0,806$	present study
internal consistency	items correlate with one another	Coefficient Alpha (Cronbach's) (a) for adaptation items that account for the same latent construct	(I) KAEVO 1.0 (II) adaptation items of KAEVO 2.0 (III) mutation items of KAEVO 2.0	(I) 1056 (II & III) 398	Good reliability for (I) $\alpha = 0,890$ (II) $\alpha = 0,751$ (III) $\alpha = 0,851$	(I) Beniermann, 2019 (II & III) present study

(Continued)

Table 9. Continued.

source	description	methodology	referring to instrument	*N*	results	references
		Coefficient Alpha (Cronbach's) (b) tested for three different age/ education groups (KAEVO 2.0)	(I) adaptation items KAEVO 2.0 (II) mutation items of KAEVO 2.0	*(Ia) 145 (high school students)* *(Ib) 122 (undergraduates non-biology)* *(Ic) 131 (undergraduates biology)* *(IIa) 145 (high school students)* *(IIb) 122 (undergraduates non-biology)* *(IIc) 131 (undergraduates biology)*	Good reliability for (Ia) α = 0,822 (Ib) α = 0,860 (Ic) α = 0,813 Good reliability for (IIa) α = 0,730 (IIb) α = 0,781 Acceptable reliability for (IIc) α = 0,675	present study
inter-rater agreement	assessment scored consistently by different raters	Does not apply for this instrument	-	-	-	-

As in the present study, Beniermann (2019) found a significant positive correlation between knowledge about and attitudes towards evolution, whereby the strength of correlation increased with age and educational level. Overall, correlation coefficients are comparable in tendency and in strength with the previous study of Beniermann (2019) as well as with previous studies using other instruments to investigate this relationship, indicating external validity of the extended and modified instrument.

Despite examining possible consequences that might result from the use of the instrument, all different categories of sources of evidence for validity have been considered (AERA et al., 2014) to examine whether KAEVO scores are appropriate to measure knowledge about evolution as intended.

Despite test-retest reliability (stability), we took all different categories of sources of evidence for reliability into account to test for consistency of our instrument. Hence, we did not test inter-rater reliability (inter-rater agreement) either, but this source is not an appropriate measure for our instrument. The present study revealed that the items of our instrument showed reliable results based on the whole sample as well as the subgroups. Comparable to the results of the modified and extended instrument, Beniermann (2019) found that the *evolutionary adaptation and natural selection* items of KAEVO 1.0 were highly reliable for the whole sample ($\alpha = 0.890$).

Pre-existing KAEVO 1.0 items

The multiple choice items of KAEVO-A 2.0 include the potential to reveal knowledge about evolution among a range of different evolutionary concepts. The results show that most students had high knowledge in some, but limited knowledge in other evolutionary concepts. These results support our goal to effectively measure the knowledge of various evolutionary concepts by means of a preferably short instrument. Additionally, these results support the assumption that it is necessary to include different evolutionary concepts to measure the whole construct 'knowledge about evolution' with its multiple aspects. With common misconceptions as distractors, our results also allowed to investigate students' misconceptions with the valid results of items of KAEVO-A 2.0. Our results of KAEVO-C 2.0 items helped to identify heat maps as a well suiting format to display deep time understanding, as they illuminate difficulties in estimating long periods of time. Most students indicated all three events (phase of existence of humans on Earth, phase of existence of dinosaurs on Earth, and origin of life on Earth) far too early in the history of Earth. This illustrates that most students do not have a scientifically accurate understanding of deep time. With heat maps, it is possible to evaluate if students place the events in the correct relative order but also how they estimate the scale of time between these events. In contrast to multiple choice scales, a timeline without absolute dates provides the opportunity to express conceptions of deep time events.

New items in KAEVO 2.0

Overall, the newly developed items of KAEVO 2.0 improved the existing instrument with regard to content and provided valid results based on the surveyed populations. CFA revealed that the evolutionary concepts added to KAEVO 1.0 are separate and relevant factors of the construct 'knowledge about evolution.' The difficulty ranged from very difficult (items A9.1 and A9.2 on *tree reading*), medium difficult (item A10 on *speciation including variation*) to easy (item A7 on *heredity of phenotype changes*). The results of the *tree reading* items indicate that *tree reading* seems to be very difficult for students, even after secondary education.

We defined score categories for KAEVO 2.0 as well as the multiple choice (KAEVO-A 2.0) and the true/false statement part (KAEVO-B 2.0) to make comparisons between different data sets easier (see Table 10). A search for categories for other knowledge instruments only resulted in a statement from Anderson, Fisher, & Smith (2010) for the CINS, stating that '[…] anyone who scores 16/20 or higher on CINS understands natural selection quite well.' Our categories for KAEVO 2.0 are oriented towards this statement.

As previously illustrated, the true/false items of KAEVO-B 2.0 were predominantly very easy. We recommend to address the high guessing rate by setting a higher bar than usual to define high knowledge on the respective concept. The distribution of the different misconceptions can be helpful for instructors to investigate where to tackle the lack of knowledge of their students.

Application advice

The variety of instruments to assess knowledge about evolutionary concepts (see Table 1) offers various possible applications. KAEVO 2.0 can be used for high school students from grade 10 on, undergraduates (biology majors and non-majors), and also for in-service teachers. It can help instructors to get a broad overview of their students' knowledge about various evolutionary concepts and underlying misconceptions. The final version of KAEVO 2.0 can be found in the Appendix. If CFA are intended to be conducted, it should be considered that CFA cannot be conducted with item A2 and A11, as these items reflect single constructs.

For a detailed insight into misconceptions in terms of natural selection, we suggest to use the ACORNS (Nehm et al., 2012). Because of its open format, it can provide detailed results. If results are needed on conceptions about natural selection that are easy to collect and analyse, we recommend the CINS (Anderson et al., 2002) and the CANS (Kalinowski et al., 2016). GeDI (Price et al., 2014) is the best 'specialist' to get a quick insight into biology majors' conceptions about genetic drift. Using only agree/disagree statements, results can be generated fast. The MUM (Nadelson & Southerland, 2009) is, apart from KAEVO 2.0, the only instrument on macroevolution. It covers more macroevolutionary aspects than KAEVO 2.0, but is intended to be used only for undergraduates. Therefore we recommend to use it if a detailed insight into knowledge about macroevolution of undergraduates is required.

Table 10. Score categories for KAEVO 2.0, KAEVO-A 2.0, and KAEVO-B 2.0.

	KAEVO 2.0	KAEVO-A 2.0	KAEVO-B 2.0
High knowledge	23–24	12	12
Rather high knowledge	19–22	10–11	11
Moderate knowledge	15–18	8–9	9–10
Low knowledge	11–14	6–7	7–8
Very low knowledge	0–10	0–5	0–6

Limitations

The main limitation is the compromise between including several relevant evolutionary concepts and having a possibly short instrument. The number of multiple choice items was kept as low as possible and several true/false items were included to handle the length of the instrument. As a result, the guessing rate of the items is not consistent, which is why the items have to be interpreted differently regarding the grade of knowledge of a respective sample. Additionally, KAEVO 2.0 contains only few items per evolutionary concept, which is why it is not possible to provide evidence for reliability for all constructs of KAEVO 2.0. To address this problem, items on the respective constructs could be added. On the other hand, it should be considered that the instrument is already relatively long and should not be greatly extended.

For our analyses, we treated scores derived from scales as interval data, which is a common practice for such analyses. However, we are aware that this assumption may not be valid in the analysis with item response theory (Hambleton et al., 1991).

Nehm and Ha (2011) emphasised that the manner in which students respond to questions on natural selection depends on the context. We included zoological and botanical contexts, but all items refer to the gain of traits. A correlational analysis of KAEVO 2.0 with other instruments measuring knowledge about evolution (or aspects of it) could provide additional evidence for a reasonable external structure. Nevertheless, it will be difficult to put this plan into practice for the whole KAEVO 2.0 because no other instrument covers all these different evolutionary concepts. However, a correlational analysis of the *evolutionary adaptation and natural selection* items of KAEVO 2.0 with the CINS, CANS or ACORNS would be beneficial. Additionally, a correlational analysis of KAEVO 2.0 items on *speciation* and *tree reading* with the MUM instrument would give more insights on measuring aspects of macroevolution.

Conclusions

Our results indicate that KAEVO 2.0 produces valid and reliable results for different age groups and educational levels based on the surveyed populations. Instructors can assess their students' knowledge about various aspects of microevolution and macroevolution and also the underlying misconceptions using KAEVO 2.0, to make their teaching more efficient and expedient. The great advantage for instructors using KAEVO 2.0 is that one single assessment provides a broad overview of students' knowledge of various aspects of evolution. The new items turned out to enrich the existing KAEVO 1.0 by increasing the number of relevant evolutionary concepts, illustrated by the dimensionality of KAEVO-A and the mutation items.

In further research, results gathered with KAEVO 2.0 should be correlated with results collected with commonly used instruments measuring knowledge about evolution on the same population to push the convergent validation of KAEVO 2.0 and contribute to questions of evolution assessment in general. Additionally, a validation for additional education levels, such as in-service teachers, is pending.

The presented version of the instrument will be used in a multinational European comprehensive survey among college undergraduate freshmen and will be updated subsequently. We emphasise to use this instrument as a diagnostic tool to determine for instance how effective curricula are in achieving the goals of evolution education.

Note

1. Covered evolutionary concepts differing from Mead et al. (2019).

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6 Paper III

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RESEARCH ARTICLE

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European first-year university students accept evolution but lack substantial knowledge about it: a standardized European cross-country assessment

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Abstract

Background: Investigations of evolution knowledge and acceptance and their relation are central to evolution education research. Ambiguous results in this field of study demonstrate a variety of measuring issues, for instance differently theorized constructs, or a lack of standardized methods, especially for cross-country comparisons. In particular, meaningful comparisons across European countries, with their varying cultural backgrounds and education systems, are rare, often include only few countries, and lack standardization. To address these deficits, we conducted a standardized European survey, on 9200 first-year university students in 26 European countries utilizing a validated, comprehensive questionnaire, the "Evolution Education Questionnaire", to assess evolution acceptance and knowledge, as well as influencing factors on evolution acceptance.

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Results: We found that, despite European countries' different cultural backgrounds and education systems, European first-year university students generally accept evolution. At the same time, they lack substantial knowledge about it, even if they are enrolled in a biology-related study program. Additionally, we developed a multilevel-model that determines religious faith as the main influencing factor in accepting evolution. According to our model, knowledge about evolution and interest in biological topics also increase acceptance of evolution, but to a much lesser extent than religious faith. The effect of age and sex, as well as the country's affiliation, students' denomination, and whether or not a student is enrolled in a biology-related university program, is negligible.

Conclusions: Our findings indicate that, despite all their differences, most of the European education systems for upper secondary education lead to acceptance of evolution at least in university students. It appears that, at least in this sample, the differences in knowledge between countries reflect neither the extent to which school curricula cover evolutionary biology nor the percentage of biology-related students in the country samples. Future studies should investigate the role of different European school curricula, identify particularly problematic or underrepresented evolutionary concepts in biology education, and analyze the role of religious faith when teaching evolution.

Keywords: Evolution, Acceptance, Knowledge, Multilevel modeling, Socioscientific issues, Religious faith, Higher education, Europe, Assessment, Attitude

Introduction

Most experts in the fields of biology (e.g., Dobzhansky 1973) and science education (e.g., Harms and Reiss 2019) agree that evolution is crucial to understanding biology. For this reason, the assessment of acceptance and understanding of evolution is a central topic in science education research (Dunk et al. 2019). Over the last few decades, researchers from various disciplines have investigated knowledge and acceptance of evolution and their mutual relationship between different age groups and education levels (e.g., Clément 2015; Dunk et al. 2017; Fiedler et al. 2019; Ha et al. 2019; Mead et al. 2018; Romine et al. 2017; Sbeglia and Nehm 2018), as well as in the general public (Brenan 2019; European Commission 2005; Hameed 2008; Ipsos Global @dvisory 2011; Pew Research Center 2015).

The discussion of the relationship between acceptance and understanding of evolution is still ongoing because of diverging findings (Barnes et al. 2019; Dunk et al. 2019). For instance, several studies discovered a positive relationship between knowledge about evolution and acceptance of evolution (e.g., Athanasiou et al. 2012; Ha et al. 2015; Rutledge and Warden 2000), while others described only weak or even negligible relationships (e.g., Barnes et al. 2017b; Graf and Soran 2010; Torkar and Šorgo 2020). An overview of different empirical findings is available in Fiedler et al. (2019). Some studies that compared different target groups showed that the strength of the relationship is increasing with the level of education (Beniermann 2019; Kuschmierz et al. 2020b).

Although more than 300 articles on acceptance of evolution have been published to date, little consensus has emerged on the primary factors that contribute to this construct (Barnes et al. 2019). However, some studies found religiosity (Beniermann 2019; Barnes et al. 2019), understanding the nature of science (Graf and Soran 2010; Dunk et al. 2017), or attitudes towards science (Graf and Soran 2010; Großschedl et al. 2014) as predictive factors. Just recently, statistical thinking (Fiedler et al. 2019) and the perception of a personal conflict with evolution (Sbeglia and Nehm 2020) were demonstrated to influence evolution acceptance. In addition, there are some factors whose relationship with acceptance of evolution has only recently begun to be researched, for instance interest in evolution (Barnes et al. 2021a). These differences in research findings reflect the intensely debated measurement issues in evolution education (Beniermann 2019; Barnes et al. 2019; McCain and Kampourakis 2018; Mead et al. 2019; Nehm and Mead 2019; Novick and Catley 2012; Smith et al. 2016), such as the potential for biased results based on the measurement instruments used (Barnes et al. 2019), neglect of measurement standards (Mead et al. 2019), missing definitions of key constructs (Ha et al. 2021b; Konnemann et al. 2012; McCain and Kampourakis 2018), or a sole focus on natural selection while addressing the multidimensional construct of knowledge about evolution (Kuschmierz et al. 2020a). Most research in evolution education has been conducted in the United States (e.g., Miller et al. 2021), while there is comparably scarce empirical data on evolution acceptance and knowledge in Europe (Kuschmierz et al. 2020b).

Europe's situation is very diverse due to different languages, educational systems, and more fragmented research communities (Deniz and Borgerding 2018). Thus, due to a lack of standardized assessment procedures in the existing literature, a comprehensive overview of knowledge about evolution and acceptance of evolution in Europe based on comparable data is still missing (Kuschmierz et al. 2020b).

Theoretical background

Methodological issues

Most international comparative surveys measuring acceptance of evolution (Brenan 2019; Hameed 2008; Ipsos Global @dvisory 2011; Miller et al. 2006; Pew Research Center 2015) or knowledge about evolution (European Commission 2005) collected data using only one multiple-choice question with few answer options. These surveys' results may be misleading because of a limited number of answer options (true–false, e.g., in Miller et al. 2006) that forces respondents to choose between few options on a complex topic (Pobiner 2016). Until now, no international comparative study has been performed to compare the state of acceptance of evolution and knowledge about evolution employing a questionnaire, including various multiple-choice questions and rating-scale items (Kuschmierz et al. 2020b).

The distinction between acceptance of evolution and knowledge about evolution in measurement instruments is of crucial importance, since people can have scientifically correct conceptions about evolution but are still not convinced evolution is really happening (McCain and Kampourakis 2018). Another methodological issue is not to distinguish between acceptance of evolution and religious faith (e.g., Clément 2015) because the way in which the relationship of faith, evolution, and creationism is presented influences survey results (Elsdon-Baker 2015; Kampourakis and Strasser 2015).

The sole focus of several of these comparative surveys on human evolution (e.g., in Brenan 2019; Pew Research Center 2015) may lead to another bias as human evolution is known to be harder to accept (Barnes et al. 2019) and causes higher discomfort (Grunspan et al. 2021; Rughiniș 2011) than evolution of animals and plants. Sbeglia and Nehm (2020) demonstrated that personal conflict with evolution in particular impacts acceptance of human evolution.

Also, definitions of key constructs in previous studies like knowledge, understanding, attitudes, and acceptance are inconsistent and lead to different operationalizations (Ha et al. 2021b; McCain and Kampourakis 2018; Smith et al. 2016). This ambiguous use of terms could be one of the main reasons for partially contradicting results in this field of research (Konnemann et al. 2012; Mead et al. 2019; Smith et al. 2016). For example, 'acceptance' is described as belief, an affective attitude, or a cognitive construct (Konnemann et al. 2012).

'Acceptance of evolution' is the central construct of this work and describes a positive attitude towards evolution (American Educational Research Association 1999). We use the term 'attitude' to describe a connection between an entity (attitude object), and its subjective evaluation (Eagly and Chaiken 1993). Thus, an 'attitude towards evolution' describes personal evaluations about the statement that evolution occurs. A positive attitude towards evolution is called 'acceptance,' while a negative attitude is called 'rejection' (Ingram and Nelson 2006).

In our terminology, we use the term 'knowledge' instead of the common term 'understanding' because we decided to survey content knowledge. The design of this study (using quantitative methods with a large sample size) is not suitable for measuring understanding. This distinction between terms follows the definition that a "student gains knowledge (via instruction, self-study, etc.) upon which she can build understanding" (Smith and Siegel 2016).

Evolution knowledge and acceptance in Europe

Much research in evolution education has been conducted in the United States (Miller et al. 2021), possibly due to the predominant public opposition to evolution (Brenan 2019) and the long history of creationism in the country (Scott 2008). In contrast, respondents of European countries have shown comparably high acceptance of evolution (European Commission 2005; Miller et al. 2006).

Nevertheless, there are reasons for comparing European countries in a standardized way. Europe's situation is unique because of many countries in geographically little space. Additionally, European countries differ due to different languages, educational systems, and fragmented research communities (Deniz and Borgerding 2018; Kuschmierz et al. 2020b). Thus, investigating differences of knowledge about evolution and acceptance of evolution in Europe based on comparable data offers new insights for the international research community. To date, only few international comparative studies measuring acceptance of evolution or knowledge about evolution in many different countries have been performed in Europe (Clément 2015; Miller et al. 2006). Due to a lack of standardized assessment procedures in the existing literature (Kuschmierz et al. 2020b), previous results should be used with caution when trying to compare European countries as there are several limitations.

The body of existing research on evolution knowledge and acceptance in Europe also varies between both the education levels and the countries. Only in Germany, Greece, and Turkey, more than three studies on knowledge about evolution have been published between 2010 and 2020 (Kuschmierz et al. 2020b). In the same period, only five European cross-country studies on knowledge about evolution have been published, comparing two (Göransson et al. 2020; Graf and Soran 2010; Kralj et al. 2018; Pinxten et al. 2020) to four (Šorgo et al. 2014) European countries. And, there are even less studies (Clément 2015; Graf and Soran 2010) that compared samples from more than one country regarding acceptance of evolution. Between 2010 and 2020, only in four European countries (Germany, Greece, Turkey, and the United Kingdom) three or more studies on acceptance of evolution have been published (Kuschmierz et al. 2020b).

These findings indicate a research gap in Europe in terms of comparable results on evolution knowledge and acceptance in a clearly defined target group.

Relationship of evolution knowledge, acceptance, and religious faith

For decades, the science education research community has investigated how evolution knowledge and acceptance are related to each other and still there is no consensus about this relationship (Barnes et al. 2019; Dunk et al. 2019; Glaze and Goldston, 2015). Whereas some studies reveal a strong (Ha et al. 2015; Rutledge and Warden 2000; Trani 2004), or a moderate to weak positive correlation between these factors (Akyol et al. 2012; Athanasiou et al. 2012; Fiedler et al. 2019; Graf and Soran 2010; Großschedl et al. 2014; Ha et al. 2019; Nadelson and Sinatra 2009), other studies report no connection between knowledge and acceptance of evolution (Akyol et al. 2010; Athanasiou et al. 2016; Bishop and Anderson 1990; Sinatra et al. 2003; Tekkaya et al. 2012). However, primary and secondary education students often demonstrated a lacking or weak correlation between acceptance and knowledge (Kuschmierz et al. 2020b), while in most studies pre- and in-service teachers showed a moderate (e.g., Deniz and Sahin 2016) or weak (e.g., Großschedl et al. 2014) positive relationship between these variables.

Previous research in Europe revealed that religious faith and acceptance of evolution are closely related in respondents of various education levels, indicating a lower acceptance with increasing religious faith (Athanasiou et al. 2016; Betti et al. 2020; Clément et al. 2012; Deniz and Sahin 2016; Eder et al. 2011). However, previous research on the relationship between religious faith and acceptance of evolution is limited to few European countries (Kuschmierz et al. 2020b). These studies furthermore indicated differences in acceptance for diverse religious denominations (e.g., Beniermann 2019; Konnemann et al. 2016; Southcott and Downie 2012). A comprehensive European investigation of the relationship between the factors 'knowledge about evolution', 'acceptance of evolution', and 'religious faith' as well as the influence of religious denominations and differences between European countries does not exist.

Study goals

The target of this research is to investigate evolution acceptance and knowledge and their relationship using the same standardized measuring method across Europe. Our results provide information on the state of knowledge and acceptance of European students who have recently completed upper secondary education. Furthermore, this study investigates various predictors for acceptance of evolution. In the discussion, we aim to contextualize the findings by providing an overview of European school curricula regarding the extent to which they cover evolutionary biology (Additional file 2).

Research questions

1. What is the level of knowledge about evolution, acceptance of evolution, and religious faith in European first-year university students in biology and non-biology programs?
2. What is the relationship of knowledge about evolution, acceptance of evolution, and religious faith in European first-year university students in biology and non-biology programs?
3. What are the main factors influencing acceptance of evolution in European first-year university students?

Materials and methods

Research instrument

For the purpose of this study, we used parts of the "Evolution Education Questionnaire (EEQ)" (Beniermann et al. 2021b) which has been designed to assess acceptance of evolution, knowledge about evolution, and religious faith. Specifically, we analyzed the subscales KAEVO-A (Kuschmierz et al. 2020a), ATEVO (Beniermann 2019), and PERF (Beniermann 2019) of the EEQ. Unlike most instruments in this field of research (Kuschmierz et al. 2020a)—these have been validated in the European context based on standards for educational and psychological testing (American Educational Research Association 1999), as discussed in the "Validity and reliability" section. Categories to enable the standardized interpretation of the results are available for all three instruments (Beniermann et al. 2021b; Kuschmierz et al. 2020a).

Knowledge about evolution

The Knowledge About Evolution 2.0 instrument (KAEVO 2.0; Kuschmierz et al. 2020a) covers the most essential evolutionary topics, including microevolution and macroevolution. This version, and also its predecessor KAEVO 1.0, were used to measure knowledge about evolution in previous studies (KAEVO 1.0; Beniermann 2019, KAEVO 2.0; Kuschmierz et al. 2020a, Torkar and Šorgo 2020). The instrument consists of three sections (A, B, and C).

KAEVO-A was utilized in this paper and contains 12 multiple-choice items on evolutionary adaptation and natural selection (four items), biological fitness (one item), speciation including variation (two items), the heredity of phenotype changes (two items), human evolution (one item), and phylogenetic tree reading (two items). All of these items consist of a question (e.g., *"How did the ability to run fast evolve in cheetahs?"*) embedded in a scenario, followed by several answer options. The answering options contain distractors that reflect common misconceptions, as well as the scientifically correct option. We dichotomized the items of KAEVO-A (correct = 1; wrong/not known = 0) to generate sum scores for the analyses (score range: 0–12). According to our definition of the construct 'knowledge about evolution', a higher score means a greater knowledge about evolution.

Acceptance of evolution

The Attitudes Towards Evolution scale (ATEVO; Beniermann 2019; Beniermann et al. 2021b) is a five-point rating scale with eight items. Each item consists of a statement (e.g., *"In my personal opinion, the animals and plants we know today have developed from earlier species."*) and the five answer options are "agree", "somewhat agree", "undecided", "somewhat disagree", and "disagree." Answers are quantified by values from 1 (*absolute rejection of evolution*) to 5 (*absolute acceptance of evolution*). Total scores range between 8 (*absolute rejection of evolution*) and 40 (*absolute acceptance of evolution*) (Beniermann et al. 2021b). This is in accordance with our previous definition of the construct 'acceptance of evolution.'

To ensure content validity of the ATEVO experts from different fields have reviewed and evaluated the items (Beniermann 2019). Pre-tests with high school and university students were conducted to ensure the validity of the answer processes (American Educational Research Association 1999). Evidence for local validity and reliability for the ATEVO scale was shown based on four studies (n_{total} = 9311; Beniermann 2019). Survey populations differed in the four studies to ensure that the ATEVO scale is a suitable instrument to measure attitudes towards evolution for the general public and groups of various ages and education, as well as explicitly non-religious or religious people. In order to address these diverse groups, the ATEVO scale includes items on evolution of plants and animals as well as items with a focus on human evolution that are known to be harder to accept (Barnes et al. 2019). This approach is especially useful when surveying the partly rather secular samples from different European countries (Beniermann et al. 2021b).

Religious faith

The Personal Religious Faith scale (PERF; Beniermann 2019; Beniermann et al. 2021b) is a five-point rating scale with ten items. Each item consists of a statement (e.g., *"I feel that God exists."*) and five answer options from "agree" to "disagree". Answers are quantified by values from 1 (*not religious*) to 5 (*very religious*), while total scores range between 10 (*not religious*) and 50 (*very religious*) (Beniermann et al. 2021b). The PERF scale, based on the same measurement standards and procedure as described above for the ATEVO scale, produces valid and reliable results (Beniermann 2019). It was created to measure religious faith independent from the respondents' denomination (Beniermann 2019).

Additional factors

In addition to the three main scales of this study, participants had to provide information on their age, sex, interest in biology as well as their denomination. Interest in biology was measured with a rating scale item. Participants were asked to rate their individual interest in biology on a 7-point scale from "very low" to "very high". To indicate their denomination, participants were asked to choose one of the following: Orthodox, Catholic, Christian free churches, Protestant, Muslim (Sunni, Alevi, or Shiite), Jewish, Hindu, Buddhist, Other, or None.

Sample

We aimed for a broad sample of European University students, including as many European countries as possible, to cover the diversity of Europe. In order to handle the varying total numbers of students in different European countries, a minimum sample size of $n = 150$ was negotiated with stakeholders in smaller European countries. As a stratified sampling strategy was not possible due to practical reasons of the national stakeholders, we applied a convenience sampling strategy to also include small European countries as well as less research-intensive countries.

In total, 11,723 first-year university students from 26 European countries voluntarily participated in the study. We chose first-year university students who had recently finished upper secondary education to generate a comparable target group. To learn about the status of knowledge about evolution and acceptance of evolution of students after finishing secondary education in Europe, first-year university students are a suitable sample that is easy to access. The alternative option to survey high school students was not feasible, since the access was not possible in all countries, for instance because high school students have to take important exams in the last weeks of school. Surveying high school students would have decreased the sample size and the number of participating countries substantially.

We excluded all participants who were not enrolled in the first semester, were older than 25 years or graduated from upper secondary education more than 2 years before the survey. Additionally, participants who spent 2 or more years in a country other than the surveyed country while in upper secondary education were excluded before the analyses. The resulting sample size after exclusion was 9200 (see Fig. 1). We targeted students enrolled in a biology-related university program but also surveyed non-biology students for comparison (list of biology-related university programs in Additional file 1).

Data collection

The English version of the instrument was translated into the participating countries' local languages—23 in total. We ensured the translations' quality by reverse translation of the questionnaire via national experts in the field of biology or biology education. The data were collected at European universities ($N=84$) at the beginning of the respective semesters/terms. We used a paper–pencil format because we wanted the voluntary respondents to fill the questionnaire in a standardized way in class, lasting about 30 min. The students were supervised while filling out the questionnaire and could not search the internet for the correct answers (in terms of knowledge about evolution) or let others fill out the questionnaire for them. The complete test process was anonymous, and the questionnaire was voluntary; the respondents received no incentives for completing it. Employing uniform survey instructions, the people handing out the questionnaires to students received clear instructions for the respondents, including not to communicate with the respondents beyond the instructions.

For data analysis, we separated the biology-related and non-biology students. This made it possible to compare the results of the respective subgroups in different European countries.

Overviews of the subject 'Biology' and the topic evolution in the European school curricula

To discuss the results in context and to give additional information to international readers, we reviewed the national school curricula concerning the subject "Biology" of the participating European countries, focusing on the teaching of evolution (see Additional file 2). We then summarized whether and to what extent evolution

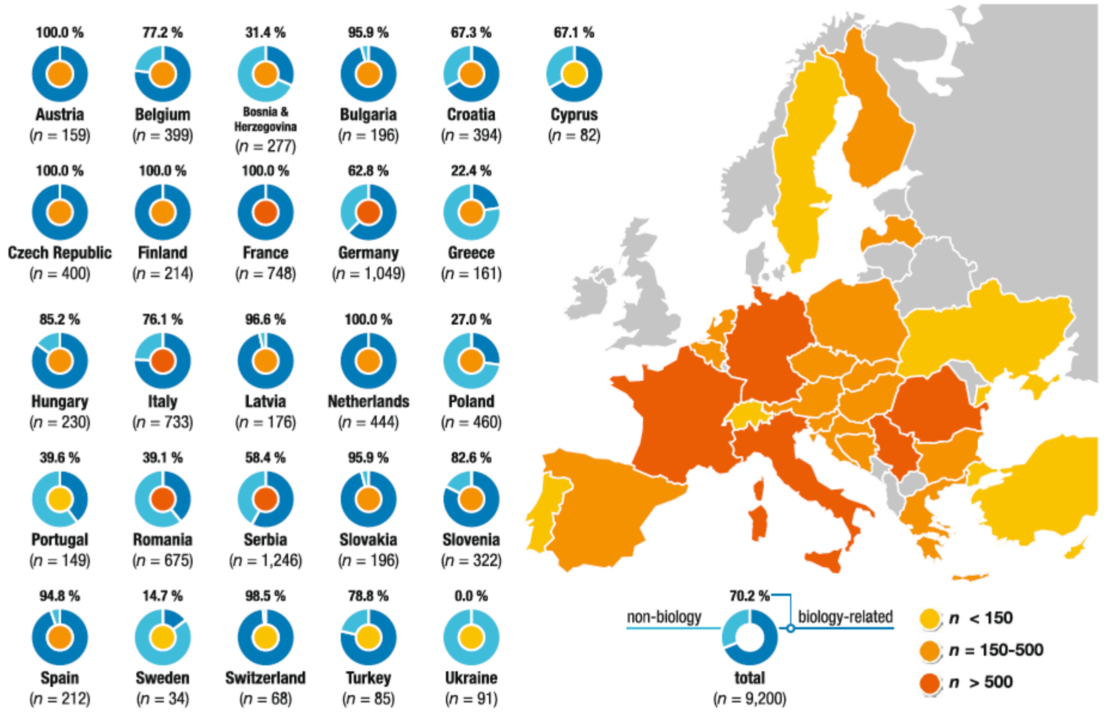

Fig. 1 Sample overview per country. Corrected sample size per country (n after excluding cases, see the "Materials and methods" section for exclusion criteria). Pie charts show the percentage ratio of biology-related to non-biology students per country. Countries in grey are not part of the study

is taught in lower and upper secondary level and which evolutionary concepts are covered.

Statistical analyses

All statistical analyses were conducted in RStudio (Version 1.3.107 based on R Version 4.0.2). The dataset (Additional file 3), as well as the R-Script (Additional files 4, 5 and 6), can be assessed in the additional information.

In the first step of the data cleaning procedure, we excluded 234 observations from the data set, all belonging to three Spanish courses that were not provided with the questions regarding their religious faith.

With the remaining data set ($n = 9200$), a missing value analysis was conducted. The percentage of missing values across the 41 items varied between 0 and 7.2%. In total 6579 observations were complete (71.5%). Another 1235 observations had only one missing value (13.4%), which, after further analyses, we assumed to occur completely at random. In contrast, 559 participants (6.1% observations) had not answered any questions concerning their religious faith, despite being provided with the complete questionnaire. We assumed a systematic pattern of missing values for this.

Considering the missing value analysis results, we decided to include all available descriptive studies and scale comparison. Furthermore, we utilized a complete case approach to perform multilevel analyses. Also, we applied the predefined exclusion criteria to filter the original dataset, setting a minimal sample size per country ($n = 150$) to enable statistical analyses in which subgroups are compared (e.g., students of different countries). Six of 26 countries were excluded from the multilevel analyses because the sample size was too small (see countries marked in yellow in Fig. 1). We reported the specific sample size for each analysis.

Mean scores and standard deviations for the three main scales were computed for the entire sample and depending on the country, university program, and sex. To compare the mean scores of knowledge about evolution, acceptance of evolution, and religious faith between students who enrolled in a biology-related university program and students who enrolled in another program, three separate *t*-tests were computed, each based on a mixed model using the country as a random effect and Satterthwaite approximation. The effect size was reported as the difference in explained variance (Aiken et al. 1991). In addition, bivariate correlations for the whole sample were used to describe the relationship between the main scales.

To compare the distributions of the sample values for acceptance of evolution, knowledge about evolution, and religious faith in the whole sample, we rescaled from the original values of the main scales to an artificial scale, ranging from 0 to 100, using the following equation:

$$y = \left(\frac{x - x_{min}}{x - x_{max}}\right) * 100 \quad (1)$$

Due to our data's hierarchical structure—students are nested in courses at universities within countries—we decided to use a multilevel modeling approach to investigate the relationship between acceptance of evolution and other variables in this dataset. However, the university-specific and country-specific sample sizes are sometimes limited, and multilevel regression models require a certain number of higher-level-units to produce unbiased parameter estimates (McNeish and Stapleton 2016; Snijders 2005). Therefore, we decided to consider only two levels: students as individual observations nested within countries.

We specified an intercept-only model as the null model and five models with an increasing number of fixed effects: Model 1 (sex and age), Model 2 (+university program and interest in biology), Model 3 (+knowledge about evolution), Model 4 (+religious faith), and Model 5 (+denomination). Additionally, the country was included in each model as a random intercept. The intercept-only model's intraclass correlation coefficient (ICC) was 0.11, which means that 11% of the overall variance can be accounted to country-specific effects ($\chi^2(1, N = 6227) = 520.65$, $p < 0.001$) and a multilevel modeling approach is appropriate (Maas and Hox 2005).

All models were estimated using the maximum likelihood method (r-Package: lme4; Bates et al. 2015). Parametric bootstrapping (number of samples: 10,000) was applied to obtain confidence intervals for both the parameter estimates of the fixed effects and the variance components. Due to the listwise deletion procedure, all models were estimated with a sample size of $n = 6227$ level-1 units (students) and $n = 20$ level-2 units (countries). Using the same sample for all models allowed us to compare the models directly via likelihood-ratio tests. Additionally, we evaluated and compared the models based on their Akaike information criterion (AIC), Bayesian information criterion (BIC), and Pseudo-R^2 values. A decrease in AIC and BIC between two subsequent models indicates a better fit of the latter. R^2_m (marginal) represents the proportion of variance explained by fixed factors. R^2_c (conditional) represents the proportion of variance explained by both fixed and random factors (Johnson 2014; Nakagawa and Schielzeth 2013).

We tested the models for multivariate normality of their residuals, as well as for homoscedasticity and multicollinearity. Multicollinearity was not an issue, as the explanatory variables' VIF values ranged between 1 and 1.4. However, the residuals' distribution was significantly left-skewed, and visual analyses of the quantile–quantile-plots (QQ-plots) indicated heteroscedastic residuals due to a ceiling effect. We used the package "robustlmm" (Koller 2016) and a Design Adaptive Scale approach to obtain robust parameter estimates and evaluate if the models' parameter estimates vary significantly from the initial non-robust models. We found minimal variations in the parameter estimates and reasonably narrow confidence intervals of the non-robust models' parameter estimates. Thus, we decided to report the results of the initial models.

Our initial plan was to account for interactions between the explanatory variables and allow the regression slopes for religious faith to vary randomly in two additional models.

As both models either did not converge properly (random slope model) or yielded biased parameter estimates due to multicollinearity (interaction model with VIF scores above 5), we decided to exclude them from the results.

Table 1 Principal Axis Factor loadings of the ATEVO and PERF scale

ATEVO		PERF	
Item Nr	**Factor loading**	**Item Nr**	**Factor loading**
E1	0.49	F1	0.90
E2	0.53	F2	0.91
E3	0.60	F3	0.85
E4	0.45	F4	0.90
E5	0.55	F5	0.83
E6	0.38	F6	0.82
E7	0.68	F7	0.87
E8	0.49	F8	0.90
		F9	0.84
		F10	0.86

Acceptance of evolution (ATEVO): $n = 8737$. Extraction method Principal Axis Factoring. Factor 1 = 2.23 (28% variance). KMO (Kaiser–Meyer–Olkin Test) = 0.79. Religious faith (PERF): $n = 8529$. Extraction method Principal Axis Factoring. Factor 1 = 7.55 (76% variance). KMO = 0.96

Validity and reliability

All elements of the EEQ instrument have been validated in an iterative process, and evidence for validity and reliability has been provided in previous studies (Beniermann 2019; Kuschmierz et al. 2020a).

In addition, the KAEVO instrument has been introduced with a four-dimensional structure for KAEVO-A (Kuschmierz et al. 2020a). Factor analysis for the present study sample confirmed this structure.

In previous studies (Beniermann 2019), the ATEVO scale has shown a unidimensional or two-dimensional structure for different samples. Principal Axis Factoring (PAF) for ATEVO and PERF revealed appropriateness to treat each of them as unidimensional (Field 2009; see Table 1).

We tested evidence for the reliability of the scales via internal consistency. The PERF scale produced very high Cronbach's alpha values for the entire sample ($\alpha = 0.969$) and all single countries. The ATEVO scale had a high value for the whole sample ($\alpha = 0.739$) and acceptable-to-high values for the single countries (Table 2).

The KAEVO instrument contains several underlying constructs, which is why Cronbach's alpha is not appropriate to measure the reliability of the entire instrument (Kuschmierz et al. 2020a).

Table 2 Reliability (Cronbach's alpha) of the acceptance of evolution (ATEVO) and religious faith (PERF) scale

Countries	*N*	ATEVO α	PERF α
Austria	159	0.751	0.958
Belgium	399	0.832	0.970
Bosnia and Herzegovina	277	0.697	0.974
Bulgaria	196	0.668	0.951
Croatia	394	0.780	0.975
Czech Republic	400	0.726	0.943
Finland	214	0.728	0.955
France	748	0.636	0.969
Germany	1049	0.747	0.959
Greece	161	0.514	0.943
Hungary	230	0.768	0.967
Italy	733	0.660	0.965
Latvia	176	0.709	0.951
Netherlands	444	0.854	0.961
Poland	460	0.753	0.973
Romania	675	0.668	0.962
Serbia	1246	0.745	0.964
Slovakia	196	0.614	0.958
Slovenia	322	0.656	0.970
Spain	212	0.602	0.969
total	8691	0.739	0.969

α = Cronbach's alpha

Results

European first-year university students generally accepted evolution but lacked substantial knowledge about evolution. Moreover, students also varied much more in their knowledge about evolution and religious faith than in their acceptance of evolution

Within the investigated sample, first-year university students across Europe rather accepted evolution ($M = 32.17$, $SD = 4.94$; score range: 8–40; see Table 3).

Biology-related students accepted evolution slightly more ($M = 32.52$, $SD = 4.86$; see Table 3) than non-biology students ($M = 31.28$, $SD = 5.01$; score range: 8–40; see Table 3) but the effect size was negligible ($t(7835.83) = -8.30$, $p < 0.001$, $f^2 = 0.01$). A small number of students rejected (0.39%) or rather rejected (0.95%) evolution (according to the suggested categories in Table 4).

In contrast, students generally lacked significant knowledge about evolution, evidenced by the fact that, on average, they answered less than half of the questions in a scientifically accurate manner ($M = 5.06$, $SD = 2.57$; score range: 0–12; see Table 3). Students that were recently enrolled in a biology-related university program knew significantly more about evolution ($M = 5.53$, $SD = 2.54$; score range: 0–12; see Table 3) than new non-biology students ($M = 3.85$, $SD = 2.22$; score range: 0–12; see Table 3), with a medium effect size ($t(7799.74) = -8.93$, $p < 0.001$, $f^2 = 0.05$). However, even within the group of biology-related students, many demonstrated very low (47.4%) or low (27.1%) knowledge about evolution (see Table 4).

Overall, students identified as not rather religious ($M = 26.78$, $SD = 13.59$; score range: 10–50; see Table 3). Nevertheless, non-biology students were significantly more religious ($M = 30.82$, $SD = 13.30$; score range: 10–50; see Table 3) than biology-related students ($M = 25.11$, $SD = 13.36$; score range: 10–50; see Table 3); however, as with acceptance of evolution, the effect size was negligible ($t(8296.66) = 6.21$, $p < 0.001$, $f^2 = 0.01$). The majority of students were not religious at all (35.7%; see Table 4).

We used scaled values to standardize the different score ranges and visualize the distribution of responses (see Fig. 2). Comparing these distributions illustrated clear differences between acceptance of evolution, knowledge about evolution, and first-year university students' religious faith. Whereas few students did not accept evolution in both subgroups, the scope of knowledge about evolution was broadly distributed. The two subgroups differed most regarding their knowledge about evolution. Students with high and moderate religious faith were equally represented in the biology-related subgroup, while most students were not religious. Non-biology students with high, moderate, and low religious faith also roughly balanced each other. Still, compared to the biology-related students, there were fewer students who are not religious.

Table 3 Descriptive data of the sample

	Biology-related	Non-biology	Total
Acceptance			
M	32.52	31.28	32.17
SD	4.86	5.01	4.94
n	6056	2470	8527
t-test	− 8.30***		
Knowledge			
M	5.53	3.85	5.06
SD	2.54	2.22	2.57
n	5616	2189	7806
t-test	− 18.93***		
Religious faith			
M	25.11	30.82	26.78
SD	13.36	13.30	13.59
n	5912	2441	8353
t-test	6.21***		

Mean (*M*), standard deviation (SD), and sample size (n) for acceptance of evolution (ATEVO; Beniermann 2019): score range: 8–40; knowledge about evolution (KAEVO; Kuschmierz et al., 2020a): score range: 0–12; religious faith (PERF; Beniermann 2019): score range: 10–50; ***$p < .0.001$

Table 4 The percentage share of different categories for knowledge about evolution, acceptance of evolution, and religious faith

	Percentage (%)		
	Biology-related	Non-biology	Total
Acceptance			
Acceptance (35–40)	36.5	27.7	34.0
Rather acceptance (29–34)	44.5	45.1	44.7
Indifferent position (20–28)	17.7	25.4	19.9
Rather rejection (14–19)	0.9	1.2	1.0
Rejection (8–12)	0.3	0.5	0.4
n	6065	2470	8526
Knowledge			
High knowledge (12)	0.1	0.0	0.1
Rather high knowledge (10–11)	4.2	0.8	0.3
Moderate knowledge (8–9)	21.2	6.3	17.0
Low knowledge (6–7)	27.1	16.6	24.1
Very low knowledge (0–5)	47.4	76.3	55.5
n	5616	2189	7805
Religious faith			
Very religious (43–50)	15.0	24.7	17.8
Religious (35–42)	12.9	19.9	14.9
Indifferent position (26–34)	17.5	20.6	18.4
Not religious (18–25)	14.1	10.5	13.1
Not religious at all (10–17)	40.5	24.3	35.7
n	5912	2441	8353

Acceptance of evolution (ATEVO; Beniermann 2019): score range: 8–40; knowledge about evolution (KAEVO; Kuschmierz et al. 2020a): score range: 0–12; religious faith (PERF; Beniermann 2019): score range: 10–50. Displayed are shares within categories (Beniermann 2019; Kuschmierz et al. 2020a) of ATEVO, KAEVO, and PERF

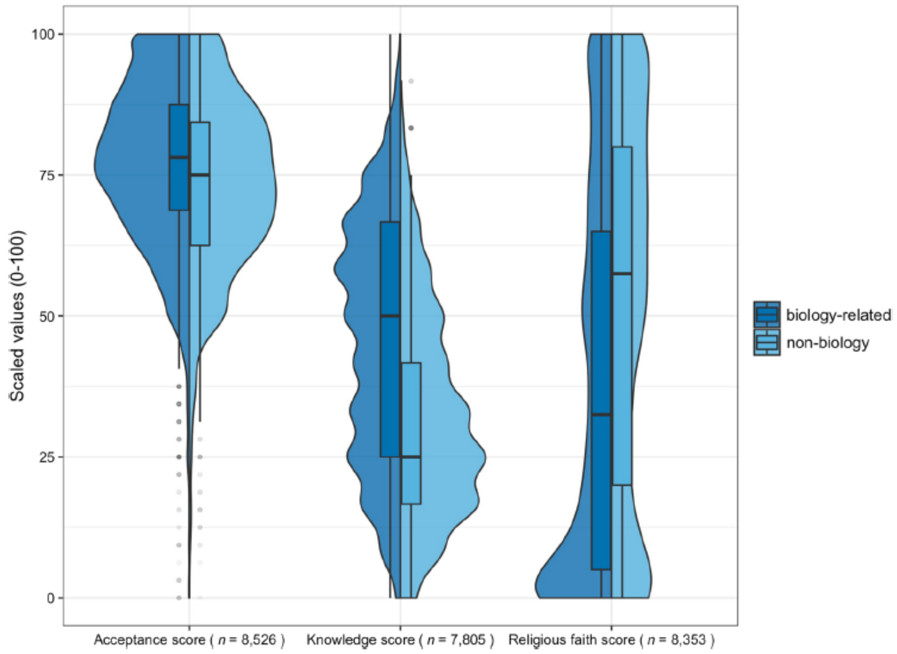

Fig. 2 Student subgroup scores for acceptance of evolution, knowledge about evolution, and religious faith. Scaled values for the entire subgroup samples are displayed. Low scores correspond to low acceptance, low knowledge, and low religious faith. Black bars represent median scores. Boxes represent Q1 and Q3 (IQR). Whiskers represent minima and maxima. Dots represent outliers. Subgroup 1 (left half of the violin plots): biology-related students; Subgroup 2 (right half of the violin plots): non-biology students. Biology-related students: acceptance of evolution, $n=6056$, $M_{scaled}=76.64$, $SD=15.20$; knowledge about evolution, $n=5616$, $M_{scaled}=46.10$, $SD=21.18$; religious faith, $n=5912$, $M_{scaled}=37.78$, $SD=33.41$. Non-biology students: acceptance of evolution, $n=2{,}470$, $M_{scaled}=72.76$, $SD=15.66$; knowledge about evolution, $n=2189$, $M_{scaled}=32.09$, $SD=18.49$; religious faith, $n=2441$, $M_{scaled}=52.05$, $SD=33.25$

Students with a lower acceptance of evolution also showed less knowledge about evolution but higher religious faith. Knowledge and acceptance were only weakly related

In our sample, acceptance of evolution (ATEVO score) and religious faith (PERF score) showed significantly negative correlations with a moderate effect.

($r_{ATEVO-PERF}=-0.37$, $p<0.01$; see Fig. 3). Similarly, knowledge about evolution (KAEVO score) and religious faith showed significantly negative correlations with a moderate effect ($r_{KAEVO-PERF}=-0.36$, $p<0.01$; see Fig. 3). In contrast, knowledge about evolution and acceptance of evolution showed significantly positive correlations with a weak effect ($r_{KAEVO-ATEVO}=0.29$, $p<0.01$; see Fig. 3).

At the country level, the samples did not differ much in acceptance of evolution but varied much more in knowledge about evolution and religious faith (see Fig. 4). Finland (100% bio-related students), the Netherlands (100% biology-related students), and Spain (94.8% biology-related students) showed the highest scores in knowledge about evolution (see Fig. 4). Furthermore, in 19 of 26 countries, students answered less than half of the questions on knowledge about evolution correctly (see Table 5).

Among European first-year university students, the country of residence had only a minimal impact on acceptance of evolution. In addition, the extent of religious faith influenced acceptance of evolution much more than knowledge about evolution

A multilevel modeling approach was used to account for variations in *acceptance of evolution* between students (Level 1) and countries (Level 2). The following explanatory variables were added sequentially: *age, sex, enrollment in a biology-related university program (yes/no),*

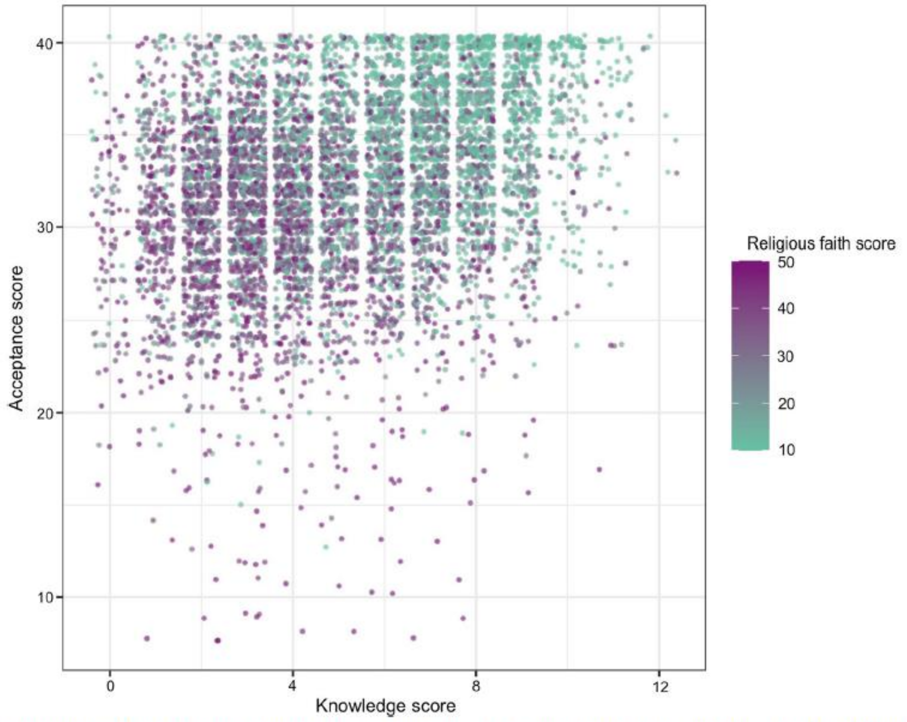

Fig. 3 Relationships between knowledge about evolution, acceptance of evolution, and religious faith. Scores (for each student) for knowledge about evolution (KAEVO score range: 0–12), acceptance of evolution (ATEVO score range: 8–40), and religious faith (PERF score range: 10–50) are displayed. Low scores correspond to low knowledge, low acceptance, and low religious faith. $r_{ATEVO-PERF} = -0.37$**, $n = 8032$; $r_{KAEVO-PERF} = -0.36$**, $n = 7260$; $r_{KAEVO-ATEVO} = 0.29$**, $n = 7434$; **Correlation is significant at the 0.01 level (2-tailed)

interest in biological topics, knowledge about evolution, religious faith, and *denomination* (see Table 6).

Overall, Model 4, which included the explanatory variables *age, sex, enrolled in a biology-related university program, interest in biological topics, knowledge about evolution, and religious faith,* provided the best model fit. It explained significantly more variance in *acceptance of evolution* (23%) than all previous models. In Model 4, 19% of the explained variance could be attributed to the explanatory variables. The largest proportion of variance explained could be attributed to *religious faith*, as Model 4 explained 11% more variance than Model 3 ($\chi^2(1, N=6227)=611.62, p<0.001$).

The model showed that very religious students accepted evolution significantly less than non-religious students. Furthermore, with each unit increase on the *religious faith* scale, the *acceptance of evolution* score dropped by 0.12 units ($b=-0.12$, $p<0.001$, 95% CI [−0.12, −0.11]).

Also, there was a significant relationship between *knowledge about evolution* and *acceptance of evolution* ($b=0.24$, $p<0.001$, 95% CI [0.19, 0.29]), indicating that students who knew more about evolution also tended to accept evolution more.

The increase in variance explained by adding *knowledge about evolution* in Model 3 was 4% ($\chi^2(1, N=6227)=169.81$, $p<0.001$). The decrease of the parameter estimate for *knowledge about evolution* between Model 3 and Model 4 indicated that some of the variance explained by *knowledge about evolution* may be related to the extent of the students' *religious faith*.

Acceptance of evolution by students increased with their *interest in biological topics*. An increase in *interest in biological topics* by one unit accompanied an increase in *acceptance of evolution* by 0.32 units ($b=0.32$, $p<0.001$, 95% CI [0.23, 0.41]). As a variable, *interest in biological topics* seemed to be more or less independent from the other investigated explanatory variables, and its estimated effect was rather stable across all models. Whether a student enrolls in a biology-related university program was not a significant predictor for *acceptance of evolution* (Model 4). Model 2 showed that students enrolled

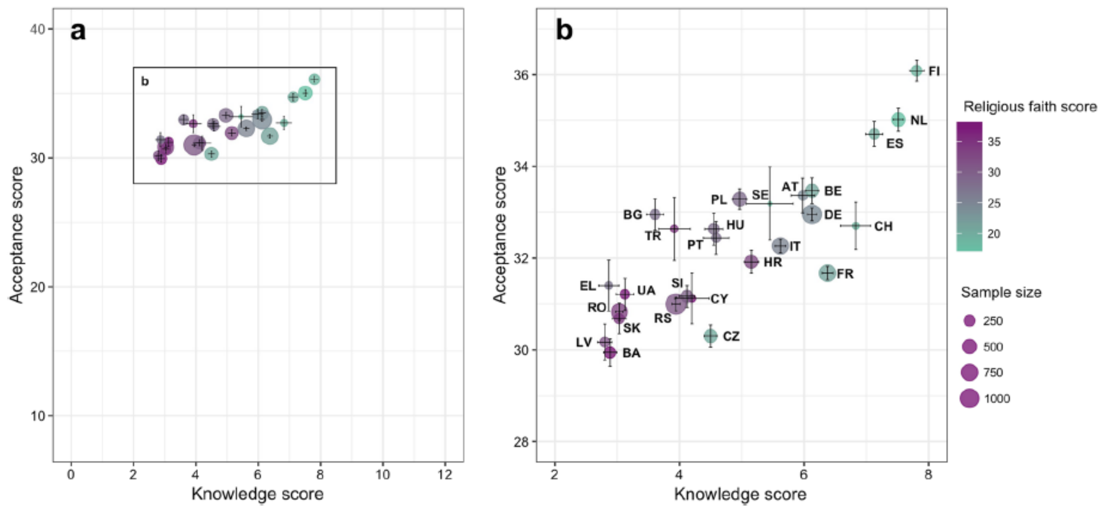

Fig. 4 Variables' relationships per country (**a** full score ranges; **b** only sections of the score ranges). In **a**, mean scores (for all students of each country) for knowledge about evolution (KAEVO score range: 0–12), acceptance of evolution (ATEVO score range: 8–40), and religious faith (PERF score range: 10–50) are displayed. In **b**, only sections of the score ranges (Knowledge score: 2–8; Acceptance score: 28–37) are displayed to make the cross-country differences in knowledge about evolution and religious faith more evident. Low scores correspond to low knowledge, low acceptance, and low religious faith. Error bars represent standard errors. Austria: AT, Belgium: BE, Bosnia-Herzegovina: BA, Bulgaria: BG, Croatia: HR, Cyprus: CY, Czech Republic: CZ, Finland: FI, France: FR, Germany: DE, Greece: EL, Hungary: HU, Italy: IT, Latvia: LV, Netherlands: NL, Poland: PL, Portugal: PT, Romania: RO, Serbia: RS, Slovakia: SK, Slovenia: SI, Spain: ES, Sweden: SE, Switzerland: CH, Turkey: TR, Ukraine: UA

in a biology-related study program tended to accept evolution more than students enrolled in a non-biology program. However, when adding *knowledge about evolution* to the model, the effect of the students' program decreased (Model 3).

Female students accepted evolution significantly less ($b = -0.59$, $p < 0.001$, 95% CI [-0.84, -0.35]) than male students for all models. However, the effect's strength decreased when adding the variables *knowledge about evolution* (Model 3) and *religious faith* (Model 4). This indicated that some of the variances in *acceptance of evolution* between men and women could be accounted for by *sex* differences in *knowledge about evolution* and *religious faith* rather than sex itself. As expected in this age-homogeneous target group (see exclusion criteria in the "Sample" section), *age* was not a significant predictor across all four models.

In general, a *students' denomination* was also not a significant predictor for *acceptance of evolution*. Model 5 explained only negligibly more variance than Model 4 ($\chi^2(1, N = 6227) = 43.51$, $p < 0.001$) and Model 4 showed the better model fit, indicated by the BIC (Table 5). However, acceptance of *Protestants* ($b = -0.67$, $p < 0.01$, 95% CI [-1.18, -0.19]) and *Muslims* ($b = -1.91$, $p < 0.001$, 95% CI [-2.78, -1.00]) was significantly lower than for *students without a denomination*.

In the best-fitting Model 4, a country's affiliation explained variance dropped to 5% (ICC = 0.05). This may indicate an interaction between the Level-1 and Level-2 explanatory variables. As our study's focus was confined to individual explanatory variables on acceptance of evolution and not country-specific factors, we did not gather additional information.

Discussion

Within the group of European first-year university students, country affiliation plays only a minimal role in accepting evolution

We provided the first standardized comparative analysis on the state of evolution knowledge and acceptance in Europe and the role of the country affiliation based on a clearly defined and comparable target group. For the first time, to our knowledge, European students were surveyed regarding their evolution knowledge and acceptance using the same multidimensional measuring instrument. Our results show that European first-year university students mostly accept evolution. The country affiliation plays only a minimal role in explaining

Table 5 Scores for acceptance of evolution, knowledge about evolution, and religious faith per country

Country	Acceptance of evolution			Knowledge about evolution			Religious faith		
	M	*SD*	*N*	*M*	*SD*	*N*	*M*	*SD*	*N*
Austria	33.37	4.75	156	5.98	2.41	145	24.47	12.64	155
Belgium	33.47	5.59	384	6.13	2.16	377	20.63	12.35	392
Bosnia-Herzegovina	29.94	4.92	222	2.89	1.78	184	38.13	12.73	210
Bulgaria	32.95	4.80	184	3.61	1.88	148	27.77	12.79	178
Croatia	31.92	4.97	373	5.15	2.30	353	32.73	14.01	350
Cyprus	31.12	4.99	75	4.2	2.51	70	38.01	9.95	74
Czech Republic	30.30	4.87	363	4.5	2.04	360	20.12	10.68	376
Finland	36.09	3.38	200	7.81	1.69	191	18.54	9.98	203
France	31.67	4.01	681	6.38	1.69	620	21.06	12.31	664
Germany	32.95	4.45	979	6.13	2.41	879	24.36	12.03	972
Greece	31.21	4.45	152	3.13	1.78	144	37.75	10.69	153
Hungary	32.64	5.30	222	4.55	2.24	212	28.04	13.76	207
Italy	32.27	4.05	695	5.62	2.32	656	25.18	11.84	648
Latvia	30.17	5.24	166	2.80	1.50	141	31.55	12.38	172
The Netherlands	35.02	5.30	431	7.51	1.71	409	17.11	10.23	430
Poland	33.29	4.82	427	4.97	2.48	397	28.42	14.26	431
Portugal	32.44	4.39	140	4.59	2.49	136	27.83	12.81	139
Romania	30.83	4.98	605	3.03	1.56	544	33.68	12.60	592
Serbia	31.00	5.11	1135	3.94	2.25	990	30.96	12.75	1068
Slovakia	30.68	4.55	188	3.03	1.49	186	34.48	13.04	183
Slovenia	31.16	4.31	298	4.12	2.20	257	29.53	13.20	300
Spain	34.71	3.97	204	7.13	1.98	190	20.02	12.16	204
Sweden	33.19	4.64	32	5.45	2.19	31	17.56	10.93	32
Switzerland	32.70	4.26	64	6.83	2.00	59	18.88	10.01	66
Turkey	32.64	6.33	69	3.92	2.35	60	35.25	13.86	71
Ukraine	31.40	5.30	82	2.87	1.52	67	27.04	13.46	83

Score ranges: acceptance of evolution: 8–40; knowledge about evolution: 0–12; religious faith: 10–50

acceptance or rejection of evolution. These two findings indicate that most of the European education systems for upper secondary education with all their differences lead to acceptance of evolution at least in university students. So far, studies showed varying results, depending on the used instrument or the surveyed country. Results of some previous studies on university students of different European countries are supported by our findings (Arthur 2013; Beniermann 2019; Betti et al. 2020; European Commission 2005; Gefaell et al. 2020; Graf and Soran 2010; Großschedl et al. 2014; Konnemann et al. 2018; Nehm et al. 2013; Southcott and Downie 2012). However, other studies revealed undecided positions or rejection of evolution among pre-service teachers in Greece (Athanasiou et al. 2012; Athanasiou and Papadopoulou 2012) and Turkey (Akyol et al. 2010, 2012; Bilen and Ercan 2016; Deniz et al. 2011; Deniz and Sahin 2016; Graf and Soran 2010; Irez and Bakanay 2011; Yüce and Önel 2015). In the present study, Greek and Turkish students mainly accept evolution, with several other countries showing less acceptance (see Fig. 4). However, the Turkish results should be interpreted with caution because of the small sample size ($n=85$). Still, our comparison of 26 European countries reveals that country affiliation plays only a minimal role in explaining acceptance or rejection of evolution.

Within our extensive European sample of first-year university students, a very small share of students rejects or rather rejects evolution based on the interpretation categories (see Table 4). These students that reject evolution could be the focus of further analyses and studies. By focusing on this group, researchers could investigate the reasons for rejection in more detail and compare predictors for acceptance of evolution with the whole sample. In summary, only a minimal number of European first-year university students reject evolution.

Table 6 Mixed effect models

	Model 1			Model 2			Model 3			Model 4			Model 5		
	Est. (b)	SE	CI_{95}	Est. (b)	SE	CI_{95}	Est. (b)	SE	CI_{95}	Est. (b)	SE	CI_{95}	Est. (b)	SE	CI_{95}
Fixed effects															
Intercept	34.18***	1.3	[31.64; 36.72]	31.72***	1.3	[29.16; 34.26]	29.37***	1.28	[26.86; 31.85]	33.36***	1.23	[30.98; 35.75]	33.12***	1.23	[30.69; 35.54]
Age	− 0.04	0.06	[− 0.17; 0.08]	− 0.04	0.06	[− 0.16; 0.09]	0	0.06	[− 0.12; 0.13]	− 0.01	0.06	[− 0.13; 0.11]	0	0.06	[− 0.12; 0.12]
Sex (male)															
Female	− 1.15***	0.13	[− 1.41; − 0.89]	− 1.15***	0.13	[− 1.42; − 0.90]	− 0.88***	0.13	[− 1.14; − 0.63]	− 0.59***	0.13	[− 0.84; − 0.35]	− 0.61***	0.13	[− 0.86; − 0.36]
University program (bio-related)															
Non-biology				− 0.33	0.18	[− 0.68; 0.01]	− 0.06	0.17	[− 0.40; 0.28]	− 0.03	0.17	[− 0.36; 0.30]	− 0.01	0.17	[− 0.34; 0.32]
Interest in biology				0.47***	0.05	[0.38; 0.56]	0.37***	0.05	[0.27; 0.46]	0.32***	0.05	[0.23; 0.41]	0.32***	0.05	[0.23; 0.41]
Knowledge							0.37***	0.03	[0.31; 0.42]	0.24***	0.03	[0.19; 0.29]	0.23***	0.03	[0.18; 0.29]
Religious faith										− 0.12***	0	[− 0.12; − 0.11]	− 0.11***	0.01	[− 0.12; − 0.10]
Denomination (none)															
Protestant													− 0.67**	0.25	[− 1.18; − 0.19]
Christian free Churches													− 0.53	0.28	[− 1.07; 0.01]
Catholic													0.29	0.18	[− 0.06; 0.65]
Orthodox													0.09	0.26	[− 0.41; 0.60]
Muslim													− 1.91***	0.45	[− 2.78; − 1.00]
Other													− 0.27	0.26	[− 0.77; 0.23]
	Std. dev		CI_{95}	Std. dev		CI_{95}	Std. dev		CI_{95}	Std. dev		CI_{95}	Std. dev		CI_{95}
Variance components															
Country (Intercept)	1.59		[1.02; 2.04]	1.32		[0.85; 1.72]	1.01		[0.63; 1.32]	0.99		[0.62; 1.29]	1.02		[0.63; 1.33]
Residual	4.63		[4.55; 4.71]	4.58		[4.50; 4.66]	4.52		[4.44; 4.60]	4.3		[4.23; 4.38]	4.29		[4.21; 4.36]
Model diagnostics															
AIC	36,849			36,698			36,530			35,920			35,889		
BIC	36,883			36,745			36,584			35,981			35,990		
X^2	73.50***			155.30***			169.81***			611.62***			43.51***		
ICC	0.1			0.08			0.05			0.05			0.05		
Fixed Pseudo-R^2	0.01			0.04			0.08			0.19			0.19		
Total Pseudo-R^2	0.11			0.11			0.13			0.23			0.23		

Dependent variable: acceptance of evolution (ATEVO). Fixed effects: age, sex (reference male), university program (reference biology-related), interest in biology, knowledge about evolution (KAEVO), religious faith (PERF), denomination (reference none). Random intercept: country. Estimates (Est.), standard-errors (SE) and 95% confidence intervals (CI_{95}) are reported for all fixed effects. Standard deviation (Std. Dev.) and 95% confidence intervals (CI_{95}) are reported for variance components. Akaike information criterion (AIC), Bayesian information criterion (BIC), intraclass correlation coefficient (ICC) as well as LRT results (X^2) are reported for all models. $n_{students} = 6227$; $n_{countries} = 20$. *** $p < .0.001$, ** $p < 0.01$, * $p < 0.05$

European first-year university students, even those enrolled in biology-related programs, often lack knowledge about evolution

The extent of knowledge about evolution is much more varied than in the case of acceptance in the investigated sample. The vast variance in knowledge is especially remarkable because the participants are homogeneous in age and educational level since they all just finished secondary education in their respective countries. Even among the students enrolled in a biology-related university program, the level of knowledge varies greatly (see Fig. 2); however, all students were surveyed before they were taught evolution at university. Previous studies found that knowledge about evolution among European university students generally increases with biology education (Kuschmierz et al. 2020b). However, some studies show low levels of expertise even for biology-related university students in Europe (Kuschmierz et al. 2020a; Pinxten et al. 2020). This disparity in the literature is supported by our results, as biology-related students knew significantly more about evolution than non-biology students, albeit the level of knowledge among biology-related students was not as high as one might expect in most countries. Additionally, the country samples differed much more in evolution knowledge than in evolution acceptance. This was true even within the biology-related students, though none had received evolution education at university previously. This effect may be explained by the varying coverage of evolution in national secondary school curricula. Before entering upper secondary education, students of almost all of the 26 surveyed European countries had been taught about evolution to some extent (Additional file 2). However, students graduating from upper secondary schools in Cyprus, Portugal, and Turkey may not have ever been taught evolution. Furthermore, during upper secondary education, differences between European countries can be found in the curricula. In some European countries, including France, Germany, the Netherlands, and Slovenia, whether students are taught about evolution, and to what extent, depends on the path they choose in secondary education. In other countries, such as Finland and Serbia, evolution is part of all students' curriculum.

Almost all surveyed students from Finland, the Netherlands, and Spain were enrolled in a biology-related study program, which may explain the high knowledge scores. Whereas evolution is compulsory in grades seven to nine in Finland, it is an elective topic for students in Spain and the Netherlands. In Latvia (96.6% biology-related students), where the students had the lowest scores in knowledge about evolution, the amount of evolution lessons is similarly dependent on students' choices. In the Czech Republic (100% biology-related students), where the students also had low scores in knowledge about evolution, students entering university usually attended compulsory evolution classes in upper secondary education. In Slovakia (95.9% biology-related students), evolution classes are also required in upper secondary education; however, evolution is not a central theme in biology education (for information on the school curricula, see Additional file 2). In our Slovakian sample, students also showed low scores in knowledge about evolution.

Hence, it appears that the differences in knowledge between countries reflect neither the number of evolution lessons in the respective school curricula nor the share of biology-related students, at least not for the national samples included in the analysis (national sample size $n \geq 150$).

However, we cannot exclude the possibility that knowledge differences are related to the structure of national school curricula since we did not investigate the number of evolution lessons the students had and how evolution was addressed during their school career. Further studies should focus more on the relationship between evolution lessons during secondary education and knowledge about evolution. Additionally, the integration of evolution in school curricula regarding the specific topics addressed and concrete learning goals should be investigated. This would help to better understand what students in different countries learn about evolution and how this impacts their knowledge about evolution. Moreover, knowledge acquisition in evolution is crucially dependent on biology teachers' content knowledge as well as pedagogical content knowledge (Kuschmierz et al. 2020a). Therefore, pre-service biology teachers' educational training should be studied as a factor in student knowledge about evolution in future research, as it differs substantially between European countries (Evagorou et al. 2015). Furthermore, there may be barriers to teach evolution in school similar to those identified for higher education (Tolman et al. 2021). These have to be taken into account as well as potential difficulties in diagnosing student's misconceptions (Fischer et al. 2021).

Religious faith predicts acceptance of evolution much more than knowledge about evolution and students' denomination

Our results revealed a positive but rather weak relationship between evolution knowledge and acceptance. Previous studies in single European countries varied from no connection between these two constructs (Akyol et al. 2010; Athanasiou et al. 2016; Graf and Soran 2010; Tekkaya et al. 2012; Torkar and Šorgo 2020), to a weak (Akyol et al. 2012; Athanasiou et al. 2012; Graf and Soran 2010; Großschedl et al. 2014; Nehm et al. 2013) or moderate

(Buchan 2019; Deniz and Sahin 2016; Großschedl et al. 2018; Mantelas and Mavrikaki 2020; Stanisavljevic et al. 2013) positive relationship. Furthermore, we found a negative correlation with a moderate effect between the religious faith and acceptance of evolution, which was also identified in previous studies across Europe (Annaç and Bahçekapılı 2012; Athanasiou et al. 2012; Beniermann 2019; Betti et al. 2020; Deniz et al. 2011; Deniz and Sahin 2016; Graf and Soran 2010; Southcott and Downie 2012).

In our study, religious faith influences acceptance of evolution much more than any other factor tested, including knowledge about evolution. Although religious faith alone cannot sufficiently explain the rejection of evolution (Beniermann 2019; McCain and Kampourakis 2018), it plays a vital role as a predictor within the group of students that identify as somewhat religious. It was shown that religious faith predicts the level of evolution acceptance for religious people regardless of other factors that have been shown to influence evolution acceptance for other samples (Allmon 2011; Rissler et al. 2014). The interaction of science and religion is a very sensitive issue, and instructors are often reluctant to discuss this topic with their students (Barnes and Brownell 2016; Southerland and Scharmann 2013). However, especially in rather religious regions, evolution education highly benefits from a cultural sensitivity and awareness of instructors (Barnes and Brownell 2017). One way to accomplish this is the use of the Religious Cultural Competence in Evolution Education framework (Barnes and Brownell 2017) that in particular addresses the competence to bridge cultural differences and enable effective communication with students with other cultural backgrounds than the instructor's. This approach might increase acceptance of evolution by reducing the perceived conflict between religion and evolution (Barnes and Brownell 2017), as this perceived conflict was demonstrated to impact evolution acceptance (Barnes et al. 2021b; Sbeglia and Nehm 2020). Moreover, addressing the compatibility between evolution and religion (Barnes et al. 2017a; Southerland and Scharmann 2013; Yasri and Mancy 2016), for instance, by referring to religious authorities and role models when teaching evolution (Holt et al. 2018; Mead et al. 2017), could reduce the students' conflict between these two topics. Thus, to foster evolution acceptance during teaching and increase the level of knowledge about evolution, teachers should be enabled to discuss the relationship between evolution and religion with their students and avoid the assumption that people, who accept evolution, are necessarily atheistic because it is associated with lower evolution acceptance for religious persons (Barnes et al. 2020). This might support learners to develop the competence to make sound judgments about the compatibility of evolution and religion (Mead et al. 2018).

It was previously shown that acceptance of evolution differs between denominations for university students in Austria, Germany, and the UK. Students without a denomination showed the highest scores (Beniermann 2019; Konnemann et al. 2016; Lammert 2012), while Christian Free Churchers (Beniermann 2019; Konnemann et al. 2016) and Muslims (Eder et al. 2011; Fenner 2013; Lammert 2012; Southcott and Downie 2012) showed the lowest scores. In agreement with those findings, in our study, Muslims accepted evolution significantly less than students without a denomination. In contrast to previous studies, however, Christian Free Churchers did not accept evolution significantly less than non-affiliated students, while Protestants showed significantly lower acceptance towards evolution. The different meanings of Free Churches as organizational structures across Europe (Elwert and Radermacher 2017) could explain this or because fundamental Evangelical religious practices are represented within Protestant communities in many European countries (Elwert and Radermacher 2017). However, the model fit decreased when adding denominations, indicating that denomination per se is not a significant predictor for accepting evolution, at least not in our sample. This finding agrees with previous studies, which revealed that the observed differences in acceptance of evolution between countries are mostly due to national socio-cultural background rather than denomination (Clément et al. 2012; Clément 2015).

In this sample, students' acceptance of evolution increased with their interest in biological topics. Although it is known that interest can foster the motivation to learn a topic (Harackiewicz et al. 2016; Hidi and Harackiewicz 2000), there is very little research on the interest in evolution (Barnes et al. 2021a; Ha et al. 2012a). In a previously conducted study, Korean and US biology majors and non-majors college students were assessed on acceptance of evolution, knowledge about evolution, interest in evolution, and religiosity (Ha et al. 2012a). Korean college students showed higher knowledge about evolution and acceptance of evolution but lower religiosity and interest in evolution as US college students. This finding seems to contradict our finding that interest in evolution increases with accepting evolution. However, the role of interest for accepting evolution should be the focus of future studies.

Within the investigated sample, female students accept evolution less than male students. This is consistent with previous findings that showed the differences in acceptance of evolution are most likely related to the different degrees of religious faith between women and men (Beniermann 2019). However, in a recent study on Greek biology university students, differences in evolution acceptance between genders were observed even after controlling for religiosity (Mantelas and Mavrikaki 2020). Although the gender gap in religious faith is well known and consistent across Western countries and especially Christian cultures (Pew Research Center 2016; Sammet 2017), the existence of a gender gap in evolution acceptance and possible rationales could also be the focus of future studies.

Limitations

We acknowledge limits to our data's generalizability due to the differences in sample sizes and shares of biology-related and non-biology students within the surveyed countries. Even though our samples are not representative of single countries, our findings still offer added value. The large total sample size and the standardized comparison basis provide essential insights into European first-year university students' acceptance and knowledge about evolution. In contrast to other comparative surveys (Brenan 2019; Ipsos Global @dvisory 2011; Miller et al. 2006; Pew Research Center 2015), we gathered data with the same validated instrument, including various multiple-choice questions.

The research instrument was translated into 23 languages to be able to survey the respondents in their native language and the translation process is a source of potential bias, which we addressed by retranslating the questionnaire with the help of national experts in the field of biology or biology education. For translations in the future, we recommend using the *Translation-Review-Adjudication-Pre-test-Documentation* (TRAPD; European Social Survey 2014) method. This method enables the reliable identification of problematic translations (Harkness 2003).

Each subsequent model in our multilevel model analysis explained more variance in acceptance of evolution than the previous model. This suggests that more predictors could have been added to the model, such as socio-cultural factors and the 'nature of science understanding' (Akyol et al. 2010; Graf and Soran 2010; Nelson et al. 2019), 'trust in science' (Graf and Soran 2010; Großschedl et al. 2014), perceived personal conflict with evolution (Sbeglia and Nehm 2020) or statistical thinking (Fiedler et al. 2019) that have been shown to interact with acceptance of evolution.

In terms of knowledge about evolution, we are limited to the evolutionary concepts covered in the study's questionnaire: evolutionary adaptation and natural selection, biological fitness, speciation, including variation, the heredity of phenotype changes, human evolution, and tree reading. When relating knowledge about evolution to the school curricula of the respective countries, it should be noted that the educational outcomes defined in the school curricula do not necessarily reflect actual knowledge about evolution gained by average students and must be interpreted with caution. Additionally, many other factors influence educational outcomes, such as teachers' experience and knowledge of general biology, and, in particular, evolutionary biology.

Conclusions

Our results showed that country affiliation only plays a minimal role in acceptance of evolution among European first-year university students, despite the varying cultural backgrounds and education systems. It would be interesting to extend these analyses beyond a clearly defined target group to a broader sample group to determine if our results can be confirmed on a greater scale. Additionally, further investigations should focus on the limited knowledge about evolution among students in Europe and potential gaps in school curricula regarding specific evolutionary topics. Our results suggest that merely increasing the number of evolution lessons may not be effective as this is not crucial for improving students' knowledge about evolution. A more detailed and standardized comparative analysis of the European school curricula could reveal potential differences, for instance, in terms of evolutionary concepts covered and specific learning goals. By analyzing our results in the context of the respective national school curricula concerning evolution (Additional file 2), we investigate potential correlations between national school curricula and evolution knowledge and acceptance. With the recently published "FACE" (Framework to Assess the Coverage of biological Evolution by school curricula; Sá-Pinto et al. 2021b), a tool for analyzing curricula, European school curricula could be analyzed and subsequently collated with our results. Furthermore, an in-depth investigation of results concerning knowledge about particular evolutionary concepts (e.g., evolutionary adaptation and tree reading) could reveal concept-dependent difficulties in understanding that should be covered explicitly in class. Moreover, in-class activities (e.g., Sá-Pinto et al. 2021a) could also be helpful to foster the understanding of evolution.

Our finding that religious faith predicts acceptance of evolution much more than knowledge about evolution implies that, besides increasing knowledge about evolution, emphasis should be placed on the relationship between evolution and religion when fostering evolution acceptance, for instance through approaches with emphasis on reasoning and argumentation (Beniermann et al. 2021a). However, instructors are often reluctant to address this sensitive topic; thus, teaching validated modules of high didactic quality and acknowledging challenges in understanding as well as fostering cultural competence (Barnes and Brownell 2017) could reduce

teachers' uncertainty when addressing this issue with their students.

Abbreviations

α: Cronbach's alpha; AIC: Akaike information criterion; ATEVO: Attitudes towards evolution; BIC: Bayesian information criterion; CI_{95}: 95% Confidence interval; EEQ: Evolution Education Questionnaire; Est.: Estimates; FACE: Framework to Assess the Coverage of biological Evolution by school curricula; ICC: Intraclass correlation coefficient; IQR: Interquartile range; KAEVO: Knowledge about evolution; KAEVO-A: Part A of the knowledge about evolution questionnaire; *M*: Mean; *N*: Total sample size; *n*: Sample size; PAF: Principal axis factoring; PERF: Personal religious faith; Q1: Quartile 1; Q3: Quartile 3; QQ-plots: Quantile–quantile-plots; *r*: Pearson correlation; *SD*: Standard deviation; *SE*: Standard-error; TRAPD: Translation-Review-Adjudication-Pre-test-Documentation; χ^2: LRT results.

Supplementary Information

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Additional file 1. List of university programs that occur in our study and are considered as biology related.

Additional file 2. Overviews of European national school curricula concerning the subject Biology and the topic "evolution".

Additional file 3. Original data set.

Additional file 4. R-script.

Additional file 5. R-scriptdonedone.

Additional file 6. Country-specific EFA.

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Authors' contributions

PK was the principal investigator of this project. ABen, DG, and PK designed and planned the study. ABen and DG supervised this project. ABen and RP lead the working group. ABen, ÁB-R, AMo, AŠ, ANS, AU, AV, ÁZL, BC, BP, CF, CV, DC, DG, GB, GR, GT, JB-W, JF, JP, JZ, LT, LV-B, MF, MP, MS, MTS, NGea, NGer, PC, PK, PLP, RMD, RP, SD, SP, TA, UBC, XS-P, and ZN were involved in the translation process of the questionnaire. ABen, AL, AMe, AMö, ANS, AP, AŠ, AU, AV, BC, BP, CF, CV, DC, DG, GR, GT, IY, JB-W, JF, JP, JZ, MĐ, MF, MP, MS, MTS, MiV, NGea, NGer, PK, RMD, RP, SP, ST, TA, TP, US, XS-P, and ZN organized conductions of the survey with multiple departments or universities involved. AMo, AMö, DAG, ED, EM, EV, IT, KO-P, LV-B, MáV, PC, PGM, PLP, UBC, and YN provided one sample each. PK and RP (only data for Belgium) digitalized the data. ABen, ABer, and PK analyzed the data. ABer created Figs. 2, 3, and 4 for the paper. PK wrote the draft of the paper. ABen, ABer, ÁB-R, AMe, AMo, AMö, ANS, APobric, AŠorgo, AU, AV, ÁZL, BC, BP, CF, CV, DAG, DC, DG, ED, EM, EV, GB, GR, GT, IT, IY, JB-W, JF, JP, JZ, KO-P, LD, LT, LV, LV-B, MĐ, MF, MP, MS, MTS, MáV, MiV, NGea, NGer, PC, PGM, PLP, RMD, RP, SD, SP, ST, TA, TP, UBC, US, XS-P, YN, and ZN proofread the draft. ABen, ÁB-R, AMe, AMö, ANS, AŠorgo, AU, AV, ÁZL, CF, CV, DAG, DC, ED, EM, EV, GR, GT, IT, JF, JP, JZ, KO-P, LT, LD, LV, LV-B, MĐ, MF, MS, MTS, MáV, NGer, PGM., PK, RMD, RP, SD, SP, ST, TA, TP, UBC, US, XS-P, and YN were involved in writing the overview of the school curricula. All authors read and approved the final manuscript.

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Availability of data and materials

The authors declare that the data supporting the findings of this study are available within the paper and its Additional files. Raw data as well as all relevant code for data analysis are included in the Additional files.

Declarations

Ethics approval and consent to participate

The participation was voluntary and anonymous. All participants have been informed about the study's objectives and the use of the data. No harm resulted from non-participation. Since students participated voluntarily, chose to participate or not prior to the survey, we assumed implicit informed consent.

Ethical guidelines as prescribed by the European Commission (2018), the German Research Foundation (2020) and the Office for Human Research Protections (2020) have been followed during planning and conducting the study.

Consent for publication

Not applicable.

Competing interests

The author(s) declare(s) that they have no competing interests.

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Publisher's Note

7 Discussion and perspectives

The following sections contain an overall discussion of the results considering the research focus of this dissertation (Chapter 7.1) as well as a summary of the limitations (Chapter 7.2). In addition, implications for future research are presented (Chapter 7.3).

7.1 Overall discussion

The three papers published as part of this dissertation contribute to the evolution education research by filling relevant research gaps. First, based on a systematic review, a comprehensive overview was provided on how much research in Europe in terms of acceptance of evolution and knowledge about evolution has been conducted in the last decade as well as its quality in terms of measurement standards. Subsequently, a category system for interpretation of measuring results was introduced to make results gathered with different evolution knowledge and acceptance instruments comparable. Second, the KAEVO 2.0, an instrument that measures the knowledge of evolutionary concepts that are essential for understanding evolution was developed and validated for target groups of different age and education levels. Third, the first standardized European survey to assess evolution acceptance and knowledge as well as influencing factors on evolution acceptance, was conducted. Utilizing a validated, comprehensive questionnaire, the "Evolution Education Questionnaire" (EEQ; Beniermann et al., 2021), 11,723 first-year university students in 26 European countries were surveyed.

7.1.1 The state of evolution education research in Europe and resulting needs

The first research focus was to identify all relevant conducted evolution education research in Europe, to compile a systematic overview of the state of research and the resulting needs. Paper I contributes to this research focus by investigating how frequently commonly used instruments for measuring acceptance of evolution and knowledge about evolution were applied across Europe within the last decade. It was revealed that the assessment of acceptance of evolution and knowledge about evolution in Europe lacks standardization and, therefore, comparable data. To make the results gathered with different instruments more comparable, percentage-orientated score categories for the interpretation of results based on the categories published in Paper II and the MATE (Rutledge & Sadler, 2007) were introduced for the evolution knowledge and acceptance instruments most commonly used in Europe.

However, only about one-third of the reviewed studies reported evidence for validity and reliability of the used instrument, even if the original instrument had been modified or translated. This goes in line with the review of Mead et al. (2019), who also found a lack of evidence for validity and reliability for reused instruments. Moreover, the amount of conducted studies varies greatly between European countries. Consequently, the amount and quality of data from European countries differ so much that a comprehensive comparison of acceptance of evolution and knowledge about evolution with this body of research is not possible.

In summary, the data basis analyzed in Paper I is insufficient for a reliable comparison of European countries. The resulting need for standardized European cross-country assessments on acceptance of evolution and knowledge about evolution is addressed by Paper III (see Chapter 6).

7.1.2 Composition of the instrument

The second research focus of this dissertation was to compose an instrument measuring acceptance of evolution and knowledge about evolution, considering all measurement problems described in the literature (see Chapter 2.5). This instrument should be ready-to-use for target groups of different age and education levels in various countries. Papers I, II, and III contribute to this research focus. Paper I emphasizes the need for standardized research in Europe. In Paper II, a part of the resulting instrument was introduced and validated, whereas as part of Paper III, the final questionnaire, the EEQ, was introduced and translated into 23 European languages.

Paper I contributes to this research focus by emphasizing the need for standardized research (see Chapter 5). It was revealed that the diversity of used evolution knowledge and acceptance instruments makes it complicated or even questionable to compare within as well as between educational groups, educational systems, and countries. Additionally, because of the high number of languages in Europe, the instruments were often translated into the respective local language but no additional evidence for validity was provided. An instrument, which is translated and validated in multiple local languages and is easily accessible would contribute to the goal of standardized research in Europe. Paper III contributes to this goal. As part of Paper III, the questionnaire consisting of the KAEVO 2.0 and the ATEVO was extended by the PERF (Beniermann, 2019), which measures religious faith as a potential predictor for acceptance of evolution. The resulting questionnaire, the EEQ, was translated into a total of 23 European languages and published as a standardized and ready-to-use protocol (Beniermann et al., 2021).

Paper II introduced the KAEVO 2.0, which is based on the KAEVO 1.0 (Beniermann, 2019). The KAEVO 1.0 represented an appropriate basis for an instrument that measures knowledge about evolution comprehensively, as it already included numerous evolutionary concepts compared to other evolution knowledge instruments (e.g., the ECT, Bishop & Anderson, 1990; the CINS, Anderson et al., 2002; the CANS, Kalinowski et al., 2016; the GeDI, Price et al., 2014; see Chapter 2.4.1). Based on content analyses of two German school curricula as well as of common and internationally distributed textbooks (*Evolution*, Futuyma, 2013; *Campbell Biology*, Urry et al., 2017), the KAEVO 1.0 was extended and modified resulting in the KAEVO 2.0. Taking the importance of an instrument's systematic evaluation during its development into account, as emphasized by Mead et al. (2019), numerous evidence for validity and reliability was provided (see Chapter 4) to meet the quality control standards established by the American Educational Research Association (AERA et al., 2014).

It was decided to take the ATEVO (Beniermann, 2019) as the acceptance of evolution instrument for multiple reasons. First, Beniermann (2019) delivered a clear definition of *acceptance* to ensure appropriate utilization of the instrument. Second, the ATEVO, consisting of eight items, is rather short (compared to e.g. the EALS with its 104 items) and therefore well-fitting for a survey not only on acceptance of evolution, but also influencing factors and knowledge about evolution. Third, the ATEVO has been validated for target groups of different age and education levels, whereas most other evolution acceptance instruments have only been validated for narrow target groups (e.g., the EALS; see Chapter 2.4.2). Fourth, other potential sources of bias, like mixing up knowledge about evolution, religious faith, and acceptance of evolution, have been considered during the developing process (Beniermann, 2019).

Summed up, the second research focus provides a foundation for future standardized evolution education research worldwide. The EEQ is:

(1) an appropriate and sound questionnaire for multiple target groups based on the investigation of several sources of validity evidence,

(2) selective between acceptance of evolution and knowledge about evolution,

(3) comprehensive regarding the evolutionary concepts added and the integrated construct 'attitudes towards evolution of the human mind',

(4) ready-to-use in 23 European languages,

(5) easily expandable, as it can be translated into other languages by following the standardized and ready-to-use protocol (Beniermann et al., 2021; see Chapter 7.3 for details).

7.1.3 Conduction of a standardized European cross-country assessment on acceptance of evolution and knowledge about evolution

The third research focus, resulting from the requirements discussed in Chapter 7.1.1, was to conduct a standardized European cross-country assessment on acceptance of evolution and knowledge about evolution. Paper III contributes to this research focus. Following the previously mentioned measurement standards, the EEQ was applied to a clearly defined target group (first-year university students enrolled in various programs; see Chapter 6 for details).

It was shown that the students mostly accepted evolution. The country affiliation and its associated cultural differences played only a minor role in evolution acceptance. Previous studies conducted in single European countries reported varying results from the rejection of evolution or undecided positions (e.g., Akyol et al., 2012; Athanasiou & Papadopoulou, 2012; Bilen & Ercan, 2016) to acceptance of evolution (e.g., Beniermann, 2019; Betti, Shaw, & Behrends, 2020; Gefaell et al., 2020). In contrast to the high acceptance of evolution, the students, even those enrolled in biology-related programs, often lacked knowledge about evolution. Students in biology-related study programs knew significantly more about evolution (M = 5.53, SD = 2.54; score range: 0–12) than students from non-biology study programs (M = 3.85, SD = 2.22; score range: 0–12), but, in most countries, not as much as one might expect (see Chapter 6). Multilevel modeling was applied to account for variations in acceptance of evolution between students at level 1 and universities at level 2. Religious faith was revealed as the most critical factor predicting acceptance of evolution along with other factors such as knowledge about evolution or whether a student was enrolled in a biology-related study program.

In summary, it can be stated that Paper III built a novel basis for the European evolution education research community. For instance, it was shown that evolution is broadly accepted among European students who recently enrolled in a university. Additionally, new research questions arose from the results of this study, for instance why first-year university students in Europe do not know much about evolution.

7.2 Limitations

In Chapter 4-6, different limitations of the conducted research are discussed. This section gives an overview of the most substantial limitations regarding this dissertation.

7.2.1 Limitations of the composed instrument

The KAEVO 2.0 contains four items on natural selection, including different contexts in terms of zoological and botanical as well as familiar and unfamiliar contexts. However, Nehm and Ha (2011) emphasized that students also tend to respond to questions on natural selection differently in terms of trait gain and trait loss. All natural selection items of the KAEVO 2.0 refer to trait gain. This issue could be addressed by adding items to cover the trait gain versus trait loss context. However, this would extend the length of the KAEVO 2.0 even more. The decision to not include some important evolutionary concepts like *genetic drift* in the KAEVO 2.0 is based on the German school curriculum (see Chapter 4) as it was utilized as the basis for content analyses. Therefore, depending on the country and the education level, researchers might miss some concepts. The KAEVO 2.0 could be adapted with items on other evolutionary concepts in the future. However, a modular structure of the questionnaire would be best suited for this purpose, for example by adding a part D to the KAEVO 2.0 to maintain the initial structure and ensure comparability of research results.

The EEQ has been translated into 23 languages to be ready-to-use in many countries. The translation process is a source of potential bias. We addressed this with the help of national biology or biology education experts by retranslating the questionnaires. To standardize this process even more, the *Translation-Review-Adjudication-Pre-test-Documentation* (TRAPD; European Social Survey, 2014) method is recommended for future translations. Using this method, problematic translations could be identified reliably (Harkness, 2003). Also, additional sources of evidence should be examined in different European countries, to make sure that the respondents in the respective countries understand all items of the EEQ.

7.2.2 Limitations of the standardized European cross-country assessment on acceptance of evolution and knowledge about evolution

The European cross-country assessment conducted as part of this dissertation is limited in terms of the generalizability of the data. Within the surveyed countries, sample sizes and shares of non-biology students and biology-related students varied. As a result, the samples are not representative for all surveyed countries. However, the standardized

comparison and the large total sample size are still valuable giving substantial insights into the evolution knowledge and acceptance of European first-year university students.
Seven different explanatory variables were added sequentially to the multilevel model to investigate whether and to what extent they explain variances in the acceptance of evolution. However, additional variables, like sociocultural factors and 'nature of science understanding' (e.g., Urhahne et al., 2011) as well as 'trust in science' (e.g., Nadelson et al., 2014), which have been shown to interact with the acceptance of evolution (Akyol et al., 2010; Graf & Soran, 2010; Großschedl et al., 2014), also could have been surveyed to explain more variance in evolution acceptance.

7.3 Implications

This dissertation contributes to the expansion of the existing body of research on evolution education in Europe by disclosing and filling research gaps in terms of instrument quality as well as standardized research and its results. The following implications can be derived from the research conducted:
Standardized research is essential to gather valid, reliable, and comparable data. Applied instruments should always be validated newly for the intended target group (Mead et al., 2019). For this reason, a standardized and ready-to-use protocol has been published for the EEQ (Beniermann et al., 2021), the questionnaire that has been composed as part of this dissertation. The application advice encompasses survey instructor guidelines, a spreadsheet for data entry, data preparation advice, calculation instructions, score categories for interpretation of results for all parts of the EEQ, and instructions for future translations of the EEQ. Using this advice, future researchers from around the world could take up the standardized European cross-country assessment and compare their results to the results that have been implemented as part of this dissertation.
Although this dissertation provides the first standardized European cross-country comparison in terms of evolution knowledge and acceptance of a clearly defined target group, it can only serve as a basis for European evolution education research that should be conducted in the future. Showing that country affiliation plays only a minimal role in the acceptance of evolution among European first-year university students, it would be of interest to investigate if this is also true for a broader sampling group. Additionally, the reason for the predominant lack of evolution knowledge among university students should be further investigated. The data gathered in Paper III could be used to compare students' knowledge of single evolutionary concepts. Also, the proportion of different

alternative conceptions could be investigated. In doing so, concept-depending difficulties in understanding could be revealed and, in a next step, compared to evolutionary concepts in the respective school curricula of European countries.

A detailed and standardized comparative analysis of the European countries' school curricula could help to understand the role of school curricula in the context of knowledge about evolution. The recently published "FACE" (Framework to Assess the Coverage of biological Evolution by school curricula; Sá-Pinto et al., 2021), an instrument for curricula analysis, could be used to analyze European school curricula. Subsequently, this data could be collated with the results of the standardized European cross-country assessment presented in this work.

Religious faith as the main predictor for the acceptance of evolution emphasizes that it is important to investigate the relationship between evolution and religion further in terms of fostering acceptance of evolution. Different approaches were recently published (e.g., Tolman et al., 2020; Sbeglia & Nehm, 2020; Siciliano-Martina & Martina, 2019). Since instructors are often still reluctant to address this sensitive topic (Barnes & Brownell, 2016), understanding the reasons for the conflict with evolution as well as validated modules of high didactic quality could help to reduce this reluctance. The EEQ, or parts of it, could be used in these modules to query knowledge but also to encourage conversations.

Abstract

In modern biology, evolution is the key concept and thus, of great importance in biology education. It has repeatedly shown that representatives of different age groups or education levels have difficulties understanding evolutionary concepts. Also, research about the acceptance and rejection of evolution has come to the fore in recent decades. With the growing body of evolution education research, measurement issues complicate the situation in terms of the possibility to compare data of different surveys. Additionally, the discussion about influencing factors on acceptance of evolution like knowledge about evolution or religious faith has arisen and is still ongoing due to deviating results in publications.

Three papers have been published as part of this dissertation project. All three papers focus on the measurement issues in evolution education and particularly on the unclear situation of the fragmented research situation in Europe. Paper I concentrates on a systematic literature review on the state of evolution education research in Europe while taking measurement issues into account. Findings indicate a lack of standardized assessment of acceptance of evolution and knowledge about evolution across Europe and, therefore, reasonably comparable data. Paper II introduces an updated version of an instrument (KAEVO 2.0) to measure the knowledge about such evolutionary concepts that are essential for understanding evolution. Paper III takes the findings of Paper I up and provides the first standardized European cross-country assessment of evolution acceptance and knowledge. By use of a validated, comprehensive questionnaire, the 'Evolution Education Questionnaire (EEQ)' that assesses evolution acceptance and knowledge, as well as influencing factors on acceptance of evolution. 11,723 first-year university students in 26 countries were surveyed. It was demonstrated that European first-year university students in biology-related as well as non-biology related study programs generally accept evolution but lack substantial knowledge about it. A multilevel model revealed religious faith as the main influencing factor on acceptance of evolution, whereas for instance, the country's affiliation is negligible. As part of Paper III, the EEQ has been translated into 23 different languages.

Overall, this dissertation expands the existing body of research on evolution education by (1) creating a systematic overview of the state of evolution education research in Europe, (2) composing an instrument based on the investigation of several sources of validity evidence to measure acceptance of evolution and knowledge about evolution comprehensively, which is currently available in 23 languages and can be easily translated into other languages by use of a standardized ready-to-use protocol, and

(3) conducting the first standardized European cross-country assessment on acceptance of evolution and knowledge about evolution.

Zusammenfassung

Evolution ist das Schlüsselkonzept der modernen Biologie und damit auch im Hinblick auf die Bildung im Bereich der Biologie von zentraler Bedeutung. Wiederholt wurde gezeigt, dass Vertreter verschiedener Altersgruppen und Bildungsniveaus Schwierigkeiten damit haben, evolutionäre Konzepte zu verstehen. Auch die Auseinandersetzung der Wissenschaft mit Akzeptanz und Ablehnung der Evolution ist in den letzten Jahrzehnten in den Vordergrund getreten. Mit dem wachsenden Korpus der Evolutionsbildungsforschung erschweren messtheoretische Probleme die Situation im Hinblick auf die Vergleichbarkeit von Daten verschiedener Erhebungen. Auch ist die Diskussion über Einflussfaktoren, wie beispielsweise Wissen über Evolution oder religiöser Glaube, auf das Konstrukt Akzeptanz der Evolution aufgekommen und ist aufgrund abweichender publizierter Ergebnisse noch immer aktuell.

Im Rahmen dieses Dissertationsprojekts wurden drei Artikel veröffentlicht. Alle drei Artikel befassen sich mit den messtheoretischen Problemen in der Evolutionsbildungsforschung und insbesondere mit der unklaren Situation der fragmentierten Forschung in Europa. Artikel I befasst sich mit einer systematischen Literaturübersicht über den Stand der Evolutionsbildungsforschung in Europa, auch unter Berücksichtigung von messtheoretischen Problemen. Die Ergebnisse deuten darauf hin, dass es an einer standardisierten Erfassung des Wissens über Evolution und der Akzeptanz von Evolution in Europa und damit an vergleichbaren Daten mangelt. Artikel II stellt eine aktualisierte Version eines Instruments (KAEVO 2.0) zur Messung des Wissens über evolutionäre Konzepte, die für das Verstehen von Evolution essenziell sind, sowie dessen Validierung vor. Artikel III knüpft an die Ergebnisse von Artikel I an und liefert die erste standardisierte europäische länderübergreifende Erhebung mit 11.723 Erstsemesterstudierenden aus 26 Ländern. Hierzu wird ein validierter, umfassender Fragebogen, der 'Evolution Education Questionnaire (EEQ)', der Akzeptanz der Evolution, Wissen über Evolution, sowie Einflussfaktoren auf die Akzeptanz der Evolution erfasst, verwendet. Es zeigte sich, dass europäische Studienanfänger die Evolution im Allgemeinen akzeptieren, dass es ihnen aber an substanziellem Wissen darüber mangelt. Dies gilt für Studierende eines biologieverwandten Studiengangs sowie für Studierende eines Studiengangs ohne Bezug zur Biologie. Es zeigte sich, dass der religiöse Glaube der Haupteinflussfaktor für die Akzeptanz der Evolution ist, während zum Beispiel die Länderzugehörigkeit vernachlässigbar ist. Im Rahmen von Artikel III wurde der EEQ in 23 verschiedene Sprachen übersetzt.

Insgesamt erweitert diese Dissertation den bestehenden Korpus der Evolutionsbildungsforschung, indem sie

(1) einen breiten Überblick über den Stand der Evolutionsbildungsforschung in Europa schafft,

(2) ein valides und reliables Instrument zur Messung der Akzeptanz der Evolution und des Wissens über Evolution zusammenstellt, das zurzeit in 23 Sprachen verfügbar ist und problemlos mit Hilfe des standardisierten, gebrauchsfertigen Protokolls in weitere Sprachen übersetzt werden können sollte und
(3) eine standardisierte europäische länderübergreifende Erhebung zur Akzeptanz der Evolution und zum Wissen über die Evolution durchführt.

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Note: The references of paper I, II, and II can be found in the respective Chapters 4, 5, and 6.

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Der Lebenslauf wurde aus der elektronischen Version der Arbeit entfernt.

The curriculum vitae was removed from the electronic version of the paper.

Publications

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Declaration

I declare that I have completed this dissertation single-handedly without the unauthorized help of a second party and only with the assistance acknowledged therein. I have appropriately acknowledged and referenced all text passages that are derived literally from or are based on the content of published or unpublished work of others, and all information that relates to verbal communications. I have abided by the principles of good scientific conduct laid down in the charter of the Justus-Liebig-University of Giessen in carrying out the investigations described in the dissertation.

Place, Date

Paul Kuschmierz

Appendix

1. EEQ in 23 European languages: https://zenodo.org/record/4554742#.YgDpqfXMJhE
2. Additional and supplementary information of Paper I: https://evolution-outreach.biomedcentral.com/articles/10.1186/s12052-020-00132-w#Sec44
3. Supplemental material of Paper II: https://www.tandfonline.com/doi/suppl/10.1080/09500693.2020.1822561?scroll=top
4. Additional and supplementary information of Paper III: https://link.springer.com/article/10.1186/s12052-021-00158-8#additional-information